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BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

MURPHY CREEK PROJECT FLOOD STUDIES

VOLUME 1: DERIVATION OF THE PROBABLE MAXIMUM FLOOD

HYDROELECTRIC GENERATION PROJECTS DIVISION

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BRITISH COLUMBIA HYDRO AND POWER AUTHORITY
HYDROELECTRIC GENERATION PROJECTS DIVISION
DEVELOPMENT DEPARTMENT

MURPHY CREEK PROJECT FLOOD STUDIES

VOLUME 1: DERIVATION OF THE PROBABLE MAXIMUM FLOOD

MAY 1981

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Report No. H 1233

MURPHY CREEK PROJECT FLOOD STUDIES

VOLUME 1: DERIVATION OF THE PROBABLE MAXIMUM FLOOD

CONTENTS

Section Subject Page

SYNOPSIS vi

1.0 INTRODUCTION

1.1 Authority 1 - 1
1.2 Purpose and Terms of Reference 1 - 1
1.3 Scope 1 - 2
1.4 Columbia River Development 1 - 3
1.5 Project Description 1 - 4

2.0 BASIN DESCRIPTION

2.1 General 2 - 1
2.2 Climate 2 - 4
2.3 Winter Snowpack Accumulation 2 - 8
2.4 Runoff 2 - 9

3.0 REVIEW AND ANALYSIS OF THE COLUMBIA RIVER BASIN DATA

3.1 General 3 - 1
3.2 The Data Base 3 - 2
3.3 Review of Streamflow Records 3 - 2
3.4 Review and Analysis of Temperature and Precipitation Data 3 - 5
3.5 Review and Use of Snow Survey Data 3 - 7
3.6 The UBC Watershed Model 3 - 9
3.7 The UBC Flow Model 3 - 10
3.8 UBC Watershed Model Calibration 3 - 10

4.0 DERIVATION OF THE PROBABLE MAXIMUM FLOOD

4.1 General 4 - 1
4.2 Derivation of One in 1000-year Snowpacks 4 - 3
4.3 Derivation of One in 1000-year Temperature Sequences 4 - 5
4.4 Derivation of the Probable Maximum Rain (PMR) 4 - 6
4.5 Derivation of the Probable Maximum Unregulated Flood (PMUF) 4 - 8
4.6 Derivation of the Probable Maximum Regulated Flood (PMRF) 4 - 9

CONTENTS - (Cont'd)

Section	Subject	Page
5.0	SUMMARY OF FINDINGS	5 - 1
6.0	CONCLUSIONS	6 - 1
7.0	RECOMMENDATIONS	7 - 1
	REFERENCES	

TABLES

Table No.		
1-1	Proposed Outline of PMF Study	1 - 2
3-1	UBC Watershed Model Calibration, Average Seasonal Runoff, 1970 - 1977	3 - 13
3-2	UBC Watershed Model Calibration, Average Monthly Runoff, 1970 - 1977	3 - 14
3-3	UBC Watershed Model Calibration, Sub-basin Runoff for each year, 1970 - 1977	3 - 15
3-4	UBC Watershed Model Calibration, Aggregate Runoff for each year, 1970 - 1977	3 - 16
4-1	Estimated Climatological Data for PMR Event	4 - 8
4-2	Areas of the Probable Maximum Rain Isohyets	4 - 9
4-3	Unregulated Extreme Floods at Murphy Creek Project Site	4 - 11
4-4	Runoff Volume Forecasts and Required Storage Levels	4 - 17
4-5	Summary of Operating Considerations during Refill	4 - 20
4-6	Regulated Extreme Floods at Murphy Creek Project Site	4 - 23
4-7	Treaty Project and Operational Data for Murphy Creek Project PMRF	4 - 25

CONTENTS - (Cont'd)

FIGURES

Figure No.	
2-1	Map of Columbia River Basin
2-2	Location of Murphy Creek Project
3-1	Sub-division of Columbia River Drainage Area above Murphy Creek Project
3-2	Simplified Schematic of the UBC Watershed Model
3-3	Calibration of Basinwide Runoff Production above Murphy Creek - 1970
3-4	Calibration of Basinwide Runoff Production above Murphy Creek - 1971
3-5	Calibration of Basinwide Runoff Production above Murphy Creek - 1972
3-6	Calibration of Basinwide Runoff Production above Murphy Creek - 1973
3-7	Calibration of Basinwide Runoff Production above Murphy Creek - 1974
3-8	Calibration of Basinwide Runoff Production above Murphy Creek - 1975
3-9	Calibration of Basinwide Runoff Production above Murphy Creek - 1976
3-10	Calibration of Basinwide Runoff Production above Murphy Creek - 1977
3-11	Columbia River Floods at Trail (Peak vs Volume)
3-12	Columbia River Floods at The Dalles (Peak vs Volume)
4-1	Estimated Isohyetal Pattern for Probable Maximum Rain Event
4-2	Columbia River Flood Volumes at The Dalles and at Trail
4-3	Hydrographs at Murphy Creek Project for the PMUF Sequence

CONTENTS - (Cont'd)

FIGURES - (Cont'd)

Figure No.

4-4 Hydrographs at Murphy Creek Project for the PMRF Sequence

4-5 Conditions at Mica Project - 72MY01MY31 (PMUF) Sequence

4-6 Conditions at Revelstoke - 72MY01MY31 (PMUF) Sequence

4-7 Conditions at Arrow Project - 72MY01MY31 (PMUF) Sequence

4-8 Conditions at Libby Project - 72MY01MY31 (PMUF) Sequence

4-9 Conditions at Porthill - 72MY01MY31 (PMUF) Sequence

4-10 Conditions at Duncan Project - 72MY01MY31 (PMUF) Sequence

4-11 Conditions at Kootenay Lake - 72MY01MY31 (PMUF) Sequence

4-12 Conditions at Murphy Creek Project - 72MY01MY31 (PMUF) Sequence

4-13 PMRF Conditons at Mica Project - 76JL07JL27 Sequence

4-14 PMRF Conditons at Revelstoke - 76JL07JL27 Sequence

4-15 PMRF Conditons at Arrow Project - 76JL07JL27 Sequence

4-16 PMRF Conditons at Libby Project - 76JL07JL27 Sequence

4-17 PMRF Conditons at Porthill - 76JL07JL27 Sequence

4-18 PMRF Conditons at Duncan Project - 76JL07JL27 Sequence

4-19 PMRF Conditons at Kootenay Lake - 76JL07JL27 Sequence

4-20 PMRF Conditons at Murphy Creek Project - 76JL07JL27 Sequence

CONTENTS - (Cont'd)

APPENDICES

Appendix No.

A Columbia River Treaty Project Data

B UBC Watershed Model - Parameter Specifications

C Regulation of Extreme Floods

D Severity of the Probable Maximum Flood

SYNOPSIS

The Murphy Creek Project is located on the Columbia River, 3 km upstream of the city of Trail, and 23 km downstream of the city of Castlegar, which is at the confluence of the Columbia and Kootenay rivers. The objective of the study was to determine the Probable Maximum Flood for the Murphy Creek Project under pre-Columbia River Treaty, i.e. natural (1961) conditions and present-day (1981) conditions. Present-day conditions include the effect of the Treaty projects, namely, Mica, Duncan, Arrow and Libby.

The study showed that under pre-Treaty conditions, the Probable Maximum Unregulated Flood (PMUF) peak of 19 900 m^3/s at the Murphy Creek Project site could only occur in early June and that under present-day conditions, because of the high degree of regulation, the Probable Maximum Regulated Flood (PMRF) peak of 13 100 m^3/s can only occur in early August, after all the upstream reservoirs are filled. The PMRF peak is 1.25 times the highest peak discharge recorded at the project site.

The results of the study were based upon an analysis of the combined effects of snowmelt and rainfall which included computer modelling evaluations of runoff volume and timing among the tributary basins. The PMRF peak was produced by a critically-timed sequence of maximized runoff from snowmelt and a Probable Maximum Rain (PMR) event. The PMR event was timed to coincide with the refill of the Mica Project reservoir, and the peak runoff from the storm occurred immediately following reservoir refill.

The study found that the PMRF at the Murphy Creek Project site was sensitive to the way in which the Treaty projects were operated, and especially sensitive to the way in which the Mica Project was operated. The greatest regulated flows at the project site were produced when it was assumed that the refill of all the Treaty reservoirs would be completed on 31 July, the target date stipulated by the Treaty. The adoption of this regulation assumption during maximized runoff conditions in late July contributed significantly to the PMRF peak.

The assumed restrictions regarding the use of reservoir storage space at the time when the PMRF peak flow would occur were the most severe that could reasonably be expected. A "pass inflow" condition was assumed to exist at all Treaty projects, because the intentional use of reservoir surcharge space above the normal full pool operating levels was not permitted under the Treaty. The regulation assumptions thereby included a loss of natural regulation benefits that could be previously attributed to the natural surcharge that would have taken place in the Arrow Lakes during the passage of the peak flow from the PMRF event.

According to the study, the assured refill and flood control operating criteria developed under the provisions of the Columbia River Treaty would limit the maximum regulated discharges in June and July at the Murphy Creek Project site to 11 300 m^3/s. The study also concluded that with full reservoir conditions after mid-August, maximum flows from the Probable Maximum Rain (PMR) event would not exceed 11 300 m^3/s, because of the earlier depletion of the snowpack and the resulting recession of the snowmelt portion of the hydrograph; however, with recession continuing from the maximized late snowmelt, the maximum discharge at the Murphy Creek Project could reach as high as 13 100 m^3/s.

It is recommended that a peak discharge of 13 100 m^3/s be adopted as the Probable Maximum Flood at the Murphy Creek Project site.

SECTION 1.0 - INTRODUCTION

1.1 AUTHORITY

Under terms of Assignment Number 479-030, dated 30 May 1979, the Hydroelectric Design Division was requested to carry out Probable Maximum Flood (PMF) studies for the Murphy Creek project under present day and pre-treaty conditions, as outlined in a memo to H.J. Goldie from F.J. Patterson dated 30 October 1978.

1.2 PURPOSE AND TERMS OF REFERENCE

The purpose of the feasibility flood studies was:

1. To develop the Probable Maximum Flood for the Murphy Creek project on the Columbia River near Trail under pre-treaty and present day (1981) conditions.

2. To develop the regulated flood frequency curve for the project outlet facilities and diversion works. The responsibilities for the PMF study are given in the Proposed Outline for the Murphy Creek project Probable Maximum Flood Study prepared by B.C. Hydro Hydroelectric Generation Projects Division (HGPD, previously Hydroelectric Design Division) and dated 28 November 1978 (Table 1-1).

This report was jointly prepared by HGPD and by the Hydrological Consultants - Mr. A. Pipes, P.Eng., and Dr. M.C. Quick, P.Eng., of the Department of Civil Engineering, University of British Columbia.

The Hydrological Consultants were responsible for the calibration of the UBC Watershed Model for the sub-basins within the drainage area upstream of the Murphy Creek project site, for the evaluation of the runoff producing factors, and for the derivation of the estimates of the Probable Maximum Flood.

Meteorological Consultants, Mr. D. Storr and Mr. K.F. Harry, were responsible for the development of the Probable Maximum Precipitation estimates and associated regional rainfall.

HGPD was responsible for the collection, preparation and frequency analysis of basin data, for the development of severe estimates of temperature sequences and snowpack accumulation, and for the channel and reservoir routing of the sub-basin streamflows using the UBC Flow Model.

1.3 SCOPE

The U.S. Committee of the International Commission on Large Dams (1970)[1] defines the Probable Maximum Flood as follows:

> "The Probable Maximum Flood identifies estimates of hypothetical flood characteristics (peak discharge, volume and hydrograph shape) that are considered to be the most severe "reasonably possible" at a particular location, based on relatively comprehensive hydrometeorological analyses of critical runoff-producing precipitation (snowmelt if pertinent) and hydrologic factors favourable for maximum flood runoff."

The objective of the study described in this volume (Volume 1) was to establish the Probable Maximum Flood (PMF) conditions which require consideration in selecting criteria for the spillway design at the Murphy Creek project site. Other considerations involved in the spillway design, such as maximum allowable upstream levels during more frequent floods are dealt with in Volume 2 of the flood studies for the Murphy Creek project. This report deals with the derivation of severe climatological conditions which would constitute a PMF event and how the various upstream regulating reservoir and flow control facilities could be operated under the provisions of the Columbia River Treaty to produce the regulated discharge which the facilities at the Murphy Creek project site would be required to pass during a PMF.

A previous study by the U.S. Army Corps of Engineers in 1969[2] provided an estimate of the Probable Maximum Flood (PMF) near the Murphy Creek project site. The purpose was to evaluate spillway adequacy at Bonneville Dam and flood protection works in the lower Columbia River; the work was not specifically intended to establish the PMF for use in design of the Murphy Creek project. Since that 1969 study, there are considerably more streamflow and meteorological data and several of the largest floods on record occurred during the 1970s and were well documented. There was therefore a need to redevelop the PMF estimate which would be specifically applicable to the Murphy Creek project and which would fully utilize the expanded data base.

1.4 COLUMBIA RIVER DEVELOPMENT

In 1944 the governments of Canada and the United States of America referred to the International Joint Commission (IJC), the problem of determining whether more efficient use of the waters of the Columbia River system would be feasible and advantageous to both countries. To assist it in carrying out this assignment, the IJC established the International Columbia River Engineering Board (ICREB), which carried out extensive studies and analyses of the problems of the development of the Columbia River basin. The ICREB submitted its findings to the IJC in 1959.

The Columbia River Treaty was signed by representatives of Canada and the United States in 1961 and ratified in 1964. In accordance with the terms of the treaty, Canada provided 19.1 x $10^9 m^3$ of storage by constructing dams at Mica, Arrow and Duncan. Duncan Dam, the smallest treaty project, became fully operational on 31 July 1967; the Hugh Keenleyside Dam at the outlet of the Arrow Lakes became operational on 10 October 1968; Mica Dam, the largest of the treaty projects, was declared operational and commenced storing on 29 March 1973. Libby Dam, located on the Kootenai River in Montana, has been operational since 17 April 1973, and commercial generation of power began on 24 August 1975. In Canada, completion of the Canal Plant on the Kootenay River in 1976 and installation of generators at Mica Dam during 1976 and 1977 provided power benefits in Canada. Completion of the Revelstoke project, now under construction, and the proposed Murphy project which is the subject of this report, will result in a substantial increase in power benefits in Canada.

1.5 PROJECT DESCRIPTION

The proposed Murphy Creek project site is located on the Columbia River approximately 3 km upstream from the city of Trail, B.C. The drainage area above the project is 88 000 km^2 which includes the entire Kootenay River watershed in the United States and Canada and the upper Columbia River watershed. The long-term average discharge at the project site is approximately 2020 m^3/s (1913-80 period of record) and the reservoir formed by the project would have a small storage capacity of 140 x 10^6m, slightly less than an average day's inflow. The surface area of the reservoir at the normal full pool elevation would be about 15 km^2. Discharges at the site are affected by upstream reservoirs on both rivers, including storage operated under terms of the Columbia River Treaty. Appendix A contains tables of data describing the upstream projects.

The dam as planned would have a crest length of approximately 170 m at El. 428 m. The gated spillway would be designed to pass the Probable Maximum Flood without severe damage to the project and to pass all floods up to 200 year frequency without raising the water levels at the upstream end of the reservoir above the proposed normal full pool reservoir level.

A zoned earthfill dam would wrap around a concrete transition section extending from the spillway. The powerhouse would be founded on rock adjacent to the spillway with excavated approach and discharge channels designed to pass maximum turbine flows of approximately 2620 m^3/s.

TABLE 1-1

PROPOSED OUTLINE OF THE MURPHY CREEK PROJECT PMF STUDY
(28 NOVEMBER 1978)

Item	Description	Responsibility
A	Collection and review of pertinent reports on operating procedures and flood studies for the Kootenay and Columbia River projects.	HGPD
B	Preliminary screening of meteorological and streamflow data to determine stations to be used in modelling.	HGPD
C	Selection of sub-basins for modelling	HGPD
D	Preparation of area/elevation data for Kootenay River basin.	HGPD
E	Assessment of hydrological response to snowmelt and rainfall for small basins within study area using the UBC Watershed Model.	Consultant
F	Calculation of natural inflows to reservoirs using UBC Flow Model.	Consultant
G	Calibration of UBC Watershed Model for initial or, if necessary, revised set of sub-basins over a nominal 10 year period 1967 to 1977 and selected high flow years.	Consultant
H	Frequency analysis of temperature, precipitation and snowpack data.	HGPD
I	Development of extreme temperature sequences and snowpacks.	HGPD
J	Development of PMP estimates and associated regional rain.	AES
K	Calculation of extreme floods for each sub-basin.	Consultant

Table 1 - (Cont'd)

Item	Description	Responsibility
L	Routing of flood flows to determine PMF under pre-treaty conditions.	Consultant
M	Preparation of computer model for regulation of flood flows.	HGPD
N	Routing of flood flows to determine PMF under present day conditions.	HGPD
O	Assessment of results.	Consultant/HGPD
P	Report Writing.	Consultant/HGPD

SECTION 2.0 - BASIN DESCRIPTION

2.1 GENERAL

The Murphy Creek project site on the Columbia River about 3 km upstream of Trail, B.C., is 23 km downstream from Castlegar, which is at the confluence of the Columbia and Kootenay rivers. The drainage basin is located in southeastern British Columbia to the west of the Rocky Mountains, and is some 500 km inland from the Coast Mountains. The basin and its location are shown in Fig. 2-1, and the Murphy Creek project site is shown in Fig. 2-2.

The Columbia River has its source in Columbia Lake, 160 km northeast of Trail. The river flows from some 320 km along the Rocky Mountain Trench in a northwesterly direction before turning south near Mica Creek, and part of this valley is now flooded by the Mica Dam development. The river then turns south and flows a further 370 km past Revelstoke and through the Arrow Lakes to Trail.

The Kootenay River, the major tributary to the Columbia River at Castlegar, originates some 150 km north of Columbia Lake and then flows in a southeasterly direction before entering the Rocky Mountain Trench near Canal Flats, only a few kilometres south of Columbia Lake. The Kootenay River then runs south for some 240 km through the wide glaciated valley forming the Rocky Mountain Trench before turning east, and then north, through Montana and Idaho to flow into Kootenay Lake. The Kootenay River flows, and those of the Duncan and Lardeau rivers at the north end of the lake, then pass through the 45 km long western arm of the lake and flow for a further 32 km along a southwesterly route to Castlegar.

Of the total 88 000 km² Columbia River drainage area above Trail, approximately 21 000 km² lie in the Rocky Mountain Trench region. On its way south through the Revelstoke canyon, the Columbia River drains a further 8000 km² of the wettest local area in the basin before entering upper Arrow Lake 50 km south of Revelstoke. The Arrow Lakes valley above Castlegar adds another 8000 km² of high runoff yield area, contributing to a total Columbia River drainage area above Castlegar of 36 500 km².

The Kootenay River drains an area of approximately 50 000 km². The river flows south into the United States and at Libby, Montana, as the river turns north to run into Kootenay Lake, the drainage area is approximately 26 000 km². Upon re-entry to Canada, the Kootenay River drainage area is approximately 35 500 km², and the rest of the tributary area is formed by the region surrounding Kootenay Lake and by the Slocan River valley which joins the Kootenay River valley about 15 km upstream from Castlegar.

The Columbia River drainage area above the Murphy Creek project site is characterized by wide glaciated valleys and high mountain chains which cross the region along a northwest-southeast axis. The drainage boundary to the east is formed by the Rocky Mountains, and this range of high mountains, rising well over 3000 m forms the North American Continental Divide, separating rivers that flow west to the Pacific Ocean from those that flow east or north to the Atlantic and Arctic oceans. The western edge of the drainage basin is formed by the Monashee Mountains in the south and by the Cariboo Mountains in the northwestern corner of the drainage basin. Running roughly parallel between the Monashee Mountains and the Rocky Mountains are the Selkirk Mountains which separate the Arrow Lakes valley from the Kootenay Lake region, and the Purcell Mountains which separate the Kootenay Lake region from the Rocky Mountain Trench. The mountains tend to be lower in the south, but the ranges all contain peaks that rise to 3000 m, and each mountain chain forms a significant elevation barrier to the prevailing weather systems coming from the Pacific Ocean in the west.

The valley floors rise from about 425 m above sea level near Trail to 800 m near Columbia Lake. The average elevation of the 88 000 km^2 area is 1600 m. Upstream from Castlegar approximately 40 percent of the drainage area is above 1800 m whereas the Kootenay drainage area is somewhat lower with approximately 30 percent of the area above this elevation. Permanent snowfields and glaciers predominate in the northern high mountain areas above 2400 m, and about 10 percent of the Columbia River drainage area above Mica Creek exceeds this elevation. The large plateau between 1800 m and 2400 m is the major source area for the regional runoff. In the southern parts of the Kootenay River watershed there is less area above 2100 m, and this leads to lower runoff yield, earlier streamflow recession, and more variation in the runoff yields from year to year. The Kootenay River drainage area is fairly typical of the rest of the Columbia River basin in the United States of America.

Most of the watershed in Canada remains in its virgin forested state. Dense forest vegetation thins above 1500 m and tree lines lie generally in the 1800 to 2100 m elevation range. Forests cover most of the steep valley slopes and on the valley floors the trees thin to include more open area. Past glaciation of the whole region has left many valley floors filled with large natural lakes, and over the last two decades some of the valleys have become major hydroelectric and flood control reservoirs. Lake storages, such as the upper and lower Arrow Lakes and Kootenay Lake, are natural reservoirs which also induce significant storage attenuation of the snowmelt floods. Each of these lake systems cover areas of over 400 km^2.

On the Columbia River the Mica Dam project, which created the Kinbasket Lake reservoir in 1974, forms a large lake in the Rocky Mountain Trench extending 210 km from Valemont in the northwest corner of the basin to

Donald. The Revelstoke Dam project, presently under construction, will control water levels in the 130 km section of the Revelstoke canyon from Mica Dam to Revelstoke; and the Hugh Keenleyside Dam, completed in 1968, links upper and lower Arrow Lakes into a single 240 km long reservoir from Revelstoke to Castlegar.

Completion of the Libby Dam project on the Kootenai River in Montana in 1973 created the 130 km long Lake Koocanusa reservoir, extending north through the Rocky Mountain Trench to Wardner, B.C. Impounding of flood waters behind Libby Dam, and the Duncan Dam project on the Duncan River at the north end of Kootenay Lake, produce considerable regulation of water levels in the Kootenay Lake region.

2.2 CLIMATE

Precipitation in the Columbia River basin develops mainly from the flow of moist low pressure weather systems which move eastward through the region from the Pacific Ocean. In the cool winter period, large snowpacks accumulate on the middle and upper elevations in the watersheds. Summer snowmelt is reinforced by rain from frontal storm systems and from local convective storms. The basin average precipitation is more moderate than for basins of the Coast Range which is exposed to the full impact of the Pacific weather systems. Occasional moist airflows approach from the east, south, or even north, but mountain ranges extract some of this moisture before it can fall in the Columbia watersheds.

Routine weather records have been taken in the basin for about 80 years. Most climate records are daily temperature and precipitation observations, and most of these records have been obtained in the more habitable valley locations. The topography and the presence of the several large lakes exert a strong influence on the local climate, and important contrasts are observed between conditions prevailing in different parts of the basin. The climate in the 10 percent of the basin below 900 m is warmer and very much drier than higher elevations. The climate in the vicinity of upper Arrow Lakes and the Revelstoke, Mica and Duncan projects in the upper Columbia region is wetter and cooler than the remaining Columbia drainage area because of the higher surrounding mountains. The climate of the Columbia River basin is discussed in detail by Storr and Harry, meteorological consultants, in their report on Probable Maximum Precipitation in the Columbia River basin (January 1980).[3]

The primary feature of the winter period is the persistence of below freezing temperatures which results in substantial snow accumulation thoughout the region each year. Some winter rainstorms occur in the most southerly parts of the basin, but in the north precipitation is invariably in the form of snow. At the average elevation of the basin, roughly two-thirds of the annual precipitation falls as winter snow. Between the central Kootenay Lake area where the long-term average precipitation is 750 mm, and Glacier at elevation 1250 m at the northern end of the Selkirk Mountains, the precipitation doubles to 1500 mm. Annual precipitation falls below 600 mm in the lower Arrow Lakes valley, and throughout the Rocky Mountain Trench annual precipitation ranges from 400 to 500 mm. There are very few high mountain observations of summer precipitation, but annual mountain precipitation is estimated to be 1000 mm or more in the south, and is estimated to increase to 1500 mm or more in the north.

The intensity and frequency of precipitation in valley and mountain areas are quite different. The extremes of record show a ten-fold increase from an annual precipitation of 250 mm in the lowest drought year in the Rocky Mountain Trench to a record maximum 2500 mm of annual precipitation in the wettest high elevation plateau region of the Selkirk Mountains. In the East Kootenay valley, some precipitation stations are poor indicators of precipitation at the higher elevation areas which produce most of the runoff. The Kaslo Station in the

Kootenay Lake region and Fauquier in the Arrow Lakes valley are low elevation stations which do show the same variability as records at higher elevations. Data from these, and the middle elevation Glacier Rogers Pass station, were used to estimate precipitation at the higher elevations. Information from the snow survey network, which has been established for 40 years, was also used to evaluate seasonal runoff potential and seasonal patterns of runoff.

Temperatures over the basin tend to be more uniform than precipitation; with allowances for temperature lapse rates, valley station temperature records can be used to estimate temperatures at higher elevations. Examination of meteorological records for valley floor locations in the south show average June and July daily temperature maxima of close to 27°C, and average minima of 10°C. The summer climate is usually very hot and dry, and average daily temperature maxima for June and July can range from 21°C to 32°C. The range of temperature minima is smaller, from 7°C to 10°C. On individual days, the maximum temperature can rise to 38°C with a minimum of 15°C on the same day. In the northern valleys, the temperatures may be 3°C cooler, partly because of the slightly higher valley floor elevations.

The coldest month of the winter is January. In this month daily temperature maxima in the valleys are near -1°C and the minima near -6°C. In the eastern parts of the drainage basin, average winter temperature can be substantially lowered by the influx of very cold arctic air masses from the polar region. Temperature contrasts in mid-winter are far less elevation dependent than in the summer. Average winter temperatures in the northwestern section of the Rocky Mountain Trench near Valemount, B.C., are roughly the same as those at Glacier Rogers Pass (460 m higher, but farther to the south) where the average daily temperature maxima and minima are about -6°C and -15°C. In the coldest years, these temperatures can be lowered by -9°C and more when very cold Arctic air masses persist throughout the area.

Average monthly maximum temperatures are below freezing for 4 months from November through February in the north, and for only 2 months, December and January in the extreme southern parts of the basin. Average monthly minimum temperatures are below freezing for 7 months from October to April in the north, and for 5 months from November through March in the south. The transition from mid-winter to mid-summer temperatures takes place at a rate of approximately 4°C per month on daily temperature maxima and at a rate of 3°C per month on the minima. In the fall, the rate of cooling is faster than this warming trend, and from September to November average maximum temperatures fall by 7°C per month, and the minima by 4°C per month.

The variation over a period of record in monthly, seasonal and annual precipitation is much higher in the valleys than in the mountains. Since most of the runoff in the region originates in the mountain areas, it is necessary to attach more significance to the variation in the mountain areas over the winter period. The best indicator of the variation in the October to March precipitation is given by Glacier climatological records in the upper Columbia region, and these show that over an 80-year period the winter precipitation has varied from 60 percent to 150 percent of the average long-term winter precipitation. The range of summer precipitation variation is similar, and on an annual basis the total precipitation at Glacier has ranged from 65 to 140 percent of the long-term average. Valley precipitation, which is far less representative of basin-wide conditions has ranged from 30 to 180 percent of average over the winters, and from 50 to 160 percent of average over the summers of record. Precipitation in the Rocky Mountain Trench is highly variable and in summer can vary from zero to several times the monthly average.

2.3 WINTER SNOWPACK ACCUMULATION

The major source of streamflow in the Columbia River in the summer months is the large inventory of snowpack water equivalent that develops during the previous winter months. This accumulation of snowfall increases rapidly with elevation as a result of both the increasing frequency and intensity of precipitation and the extended season of freezing conditions. At the 1800 m elevation, snowpacks often continue to accumulate through the month of May, offsetting the early summer snowmelt depletions. The snowfall gradient with elevation can be further illustrated by statistics giving the normal proportion of annual precipitation that falls as snow. This proportion varies from 25 percent in the dry southern valleys to 33 percent in the northern valleys. The proportion increases markedly to 67 percent at the 1200 m range, and to 75 percent in the 2100 m range. In some years, 90 percent of annual precipitation at very high elevations falls as snow.

In years of very high winter snowfall accumulation, snowpacks in the upper Columbia region develop water equivalents of 750 mm at low elevations and 1500 mm at 1800 m elevations. In years of very low snowfall accumulation, snowpacks in the same region develop maximum water equivalents of less than 250 mm in the valleys and only 750 mm at high elevations. In the Kootenay Lake and Slocan valley regions upper elevation maximum seasonal snowpack water equivalents have ranged from 400 to 1000 mm, and in the East Kootenay region winter maxima at the upper elevations have ranged from 250 mm of water equivalent in drought years to 750 mm in very wet years.

Of particular importance to flood estimates are the differences in the average winter snowpack accumulation among the different parts of the Columbia River drainage area, and the differences in variability. In the high mountain regions of the upper Columbia, where the greatest snowfall accumulations occur, the variation from year to year in the winter snowfall is roughly two-thirds of the variation over large areas of the Kootenay River basin where snowpack accumulation is much less. For example, in the region of the Mica reservoir where there is high snowpack accumulation, annual runoff volumes are not as variable as they are in the region of the Libby reservoir where runoff is much lower.

2.4 RUNOFF

The rivers begin to rise in April after the winter months of decreasing flow, and usually peak in June, at a time when the snow cover and the temperature patterns combine to produce the most favourable combination for maximum basin-wide streamflow production.

Snowmelt runoff is the major source of streamflow, and over 60 percent of runoff in the study area occurs in the months of May, June and July. Streamflow recession along the Columbia River main stem occurs later in the summer than the recession along the Kootenay River, partly as a result of cooler temperatures in the north, but mainly because of the higher snowpacks. Tributaries in the upper Columbia region can sustain high snowmelt runoff levels well into the month of July, and, as a rule, average July runoff yields in the north are only slightly less than those in June. In the south, and especially for tributary drainages without much high elevation area, the runoff yields are smaller, and two-thirds of the annual yield occurs during the months of May and June. In the Kootenay River drainage area, July flows are well into recession and are on average only 25 percent of those in May and June.

The long-term average discharge of the Columbia River at Trail is approximately 2020 m^3/s (1913-80 period of record) and this is equivalent to an average annual yield of 740 mm of runoff over the 88 000 km^2 drainage area; the runoff yield in the months of May, June and July is about 460 mm. For pre-Treaty conditions, the peak streamflow for the Columbia River at Trail occurred between the second half of May and the first half of July. The highest flows have occurred near the middle of June. The maximum daily flow of record is 10 600 m^3/s and several other peak flows near this magnitude have occurred over the period of record. Other peak flows along the Columbia River main stem, not necessarily occurring in the same year, were 3600 m^3/s at Mica, 5300 m^3/s at Revelstoke and 5400 m^3/s at Castlegar. Peak flows recorded on the Kootenay River were 2800 m^3/s at Newgate (Canada-USA boundary), 3500 m^3/s at Porthill (USA-Canada boundary) and 4900 m^3/s at the outlet of Kootenay Lake.

The average volume yield contributions along the Columbia River main stem, expressed as a percentage of the long-term yield for the Columbia River at Trail, are 30 percent for the drainage area upstream of Mica, 40 percent at Revelstoke and roughly 55 percent at Castlegar. For the Kootenay River, yield contributions are 15 percent at Newgate, 23 percent at Porthill and 40 percent at the outlet of Kootenay Lake. The remaining 5 percent of the basin volume yield comes from the Slocan River valley and the local drainage area near Trail. In any given year the pattern of yield may be quite different from an average year. For example, in 1974 the record high volume yields in the Kootenay River basin coincided with a less than record volume yield in the Columbia; in 1972 the opposite was the case.

Summer rainfall runoff is a far more significant factor in the upper Columbia region than in the Kootenay River drainage area. Occasionally the aerial extent of summer storms is large enough for such rainfall to be the major factor producing peak discharges in the upper Columbia region. Summer rainfall contributions to runoff generally occur as short-term peaks superimposed upon high river levels caused by the snowmelt runoff. In the past, severe late summer rainstorms have not produced annual peak discharges because of the advanced stage of the snowmelt recession. In the future, such rainstorms may cause annual flood peaks because Treaty reservoir operations tend to delay the peak and prolong the recession.

Within the basin, local annual runoff yields in the Revelstoke canyon area have ranged from 1000 to 1800 mm over the local area, and, in contrast, large areas along the Kootenay River have generated annual yields from as low as 180 mm to as high as 350 mm.

Over the last 67 years, annual streamflow yields have shown less variation than annual precipitation throughout the basin. Thus, the highest annual yield at Trail of approximately 2500 m^3/s (900 mm over the basin) is 125 percent of the long-term average, and the lowest of 1300 m^3/s (500 mm over the basin) is 68 percent of the long-term average; in the same period, annual basin-wide precipitation has ranged from 65 to 140 percent of the long run average, and valley precipitation is even more variable.

SECTION 3.0 - REVIEW AND ANALYSIS OF THE COLUMBIA RIVER BASIN DATA

3.1 GENERAL

The UBC Watershed Model was used to develop a detailed understanding of hydrological processes throughout the basin and to analyse the effects of various possible climatological sequences on flood production. This model provides an analysis of snowmelt and rainfall and describes how this water runs off the watershed to tributary streams. Model calibration was based on data covering a continuous period that included some of the largest floods of record; although these large floods were not as large as those which will govern the spillway design, they displayed many of the characteristics of such extremely severe events.

Analyses of the streamflow data, the climatological data, the snow survey data and the topographical information showed that the major influences on the runoff hydrographs were the snow availability and its spatial distribution; the sequence of spring and summer temperature affecting snowmelt runoff; and the spring and summer rainfall. Summer rainfall is particularly important when the watershed is saturated and capable of converting a significant percentage of the precipitation to runoff. The relative importance of each of the major influences on runoff was determined on a daily basis through the calibration of the UBC Watershed Model and this calibration was carried out separately in each of the 12 sub-areas of the drainage basin. The sub-division of the drainage area upstream of the project site is shown in Fig. 3-1. Comparisons were made between the recorded and reconstituted daily streamflow hydrographs. The period used for comparison depended upon the data that was available in each local area, but the period 1970 to 1977 was common to all data sets. This work, along with reviews of other data and supplementary analyses, led to a more complete representation of the basin-wide processes involved in snowmelt floods and in rain-on-snow events and determined the calibration of the model parameters.

3.2 THE DATA BASE

Within the basin, climatological data has been collected for a period of 80 years, streamflows have been measured for 67 years, and snowcourse data has been collected for 40 years. In addition, during the last two decades, significant improvements to the data networks have taken place, and the expanded snow survey network and the tributary streamflow measurement program now provides detailed information on the pattern of snowpack accumulation and depletion, and on runoff patterns throughout the basin during the year. This improved coverage of the data network during the 1960s and 1970s coincided with the construction of the major hydropower dam projects along both the Columbia and Kootenay rivers and stemmed from provisions of the Columbia River Treaty to control flood flows.

With this new comprehensive data base the most recent decade coincidentally furnished the opportunity for detailed hydrologic examination of a sample of flood events (and their causative factors) which were comparable in range and magnitude to the highest and lowest floods of the century. In 1972 and 1974, new flood records were established in the upper parts of the Columbia River basin although the flood flows in the downstream parts of the basin were substantially reduced by the operation of the Columbia River Treaty projects.

3.3 REVIEW OF STREAMFLOW RECORDS

The streamflow gauging network, unlike the climatological and snow survey network, provided a direct measure of the total runoff generated in the catchment area and continuous daily records of the Columbia River flows near Trail have been maintained since 1913. The record shows that the highest mean annual flows occurred in 1954 (2540 m^3/s), 1972 (2500 m^3/s) and 1959 (2480 m^3/s). Mean annual flows between 2380 m^3/s and 2410 m^3/s occurred in four other years - 1976, 1974, 1967 and 1933. These annual flows are only 15 to 25 percent higher than the long-term average flow of 2020 m^3/s.

For the period of record, annual extremes of Columbia River discharge at Trail have ranged from 3340 m^3/s to 10 600 m^3/s. Since 1968, the flows have been increasingly regulated by newly completed upstream Columbia River Treaty projects. The highest peak daily flows of record occurred in 1961 (10 600 m^3/s), 1948 (10 400 m^3/s) and 1967 (9800 m^3/s). Measured peak flows at Trail were relatively low in 1972 and 1974 as a result of upstream flood storage control, but would have been equal to the previous extreme of record (10 600 m^3/s) had some of the Columbia River Treaty projects not been operational. Lower annual peaks of between 8800 m^3/s and 9500 m^3/s occurred in five other years - 1956, 1955, 1954, 1950 and 1913.

The period 1970 through 1977, selected for detailed hydrological analysis, contains records throughout the river gauging network of flood levels comparable in magnitude to the most extreme that have occurred since record taking began in 1913. There are no records of river discharge along the Columbia River in British Columbia prior to this date. However a long record of Columbia River discharge measurement dates back to 1879 at The Dalles in the State of Oregon. Estimates of the annual extreme of the Columbia River discharge in these lower reaches of the river have been made from river stage records dating back to 1858.

The Columbia River flood of 1894 measured at The Dalles (drainage area 614 000 km^2) is the greatest flood that is known to have occurred in the basin. Flood stage marks along the Columbia River in the State of Washington were used to estimate the peak discharges of 1894 at other locations upstream from The Dalles. The Corps of Engineers estimate of the peak flow for the Columbia River at Trail in June 1894 of 13 000 m^3/s was based on flood stage marks 16 km downstream, near the International Boundary and downstream of the confluence with the Pend-d'Oreille River. An estimate of the peak flow contribution from the 65 300 km^2 Pend-d'Oreille River is also based on flood stage marks following the flood in 1894. The maximum flows from the Pend-d'Oreille River are 5500 m^3/s in 1894 (estimated), and 4800 m^3/s in 1948. Other peak flows during the period of record from 1913 to date have either been less than, or regulated to less than 3960 m^3/s. For the Columbia River at the International Boundary (drainage area 155 000 km^2), the maximum flows are 19 300 m^3/s in 1894 (estimated), 15 600 m^3/s in 1948 and 13 900 m^3/s in 1961. Between 1938 and 1968 there were three other major floods which produced annual flood peaks of 13 100 m^3/s in 1956, 13 000 m^3/s in 1951 and 12 300 m^3/s in 1967. Between 1916 and 1940, Columbia River streamflows were measured 65 km downstream from the International Boundary at Kettle Falls, Washington (drainage area 167 000 km^2). The 1894 peak flow estimate at Kettle Falls is 19 800 m^3/s and the second highest annual peak, estimated from flood marks following the 1913 flood, was 13 300 m^3/s. Other peaks close to the 1913 flood level occurred in 1928 (13 200 m^3/s) and 1916 (12 900 m^3/s) and in 1921 the maximum discharge was 11 900 m^3/s.

The severe 1948 flood provided a better data base than the earlier ones and the 1972 and 1974 floods, which were comparable to the 1948 event, are documented even more completely. The historical records of the river gauging stations upstream of the Murphy Creek project site showed that higher flood flows occurred in the 1970 through 1977 period. Data from this period was subsequently subjected to detailed hydrological analysis by subdividing the Columbia River drainage area above Trail into 12 sub-basins. Within many of these sub-basins several major tributary records could be used as reliable indicators of the runoff. Tributary records were also reviewed to establish the uniformity of runoff production within each of these 12 sub-basins. Sub-basin hydrographs (local inflows) were obtained directly in the headwater areas, but in the downstream section of the project area, they were developed from measured flow differences and storage changes in the lakes and reservoirs.

The UBC Watershed Model was initially calibrated against tributary streamflow data as a preliminary step towards calibration of the model against sub-basin data. Data from the gauging network on small tributary streams was also evaluated for a period of fairly uniform and extreme basin-wide snowmelt in June 1974 to assess spatial patterns of snowmelt runoff and snowcover. The reservoir storage and outlet capacity characteristics of the Columbia Treaty projects were used in the analysis of regulated flows; for unregulated conditions hydrometric data describing stream velocities and stream cross sections throughout the measuring network were used to develop channel capacity relationships.

3.4 REVIEW AND ANALYSIS OF TEMPERATURE AND PRECIPITATION DATA

The climatological data and routine weather records collected in the Columbia River basin over the past 80 years provided enough information to define the temperature and precipitation regimes in each of the 12 sub-basins selected for hydrological calibration. The valley climate is fairly homogeneous throughout the region, but climatic gradients are evident between valley and mountain area. The climate characteristics in the mountain areas which produce most of the runoff must be appropriately represented in order to model the behaviour of the rivers of the region. The necessary representation of the elevation dependent variation in climate was achieved through the use of the UBC Watershed Model. The use of the model, which automatically accounts for climatic conditions by elevation zone, provided a means for evaluation of the representativeness, and hence usefulness, of different sets of temperature and precipitation data in different sub-areas in the Columbia River basin.

The mountain areas are cooler because of temperature lapse rates and they also receive greater and more frequent amounts of precipitation. Generally, the temperature patterns in the mountains can be well represented using valley temperature data with the variable lapse rate algorithm of the watershed model.

Precipitation patterns are best represented using middle elevation data, such as the data from Glacier Rogers Pass. Where such data were non-existent, valley precipitation data were used. Data from some of the valley stations, even when modified to reflect orographic enhancement, as calculated by the precipitation distribution algorithm of the UBC Watershed Model, were not used because the local conditions were not sufficiently representative of higher elevation conditions.

The final adoption of a given set of climatological records in the model calibration for sub-basins was made on the basis of the ability of the analysis to replicate both the historical streamflow response from snowmelt and rainfall, and by its ability to reproduce the seasonal patterns of winter snowpack accumulation and depletion. Snowpack accumulation and depletion was indicated by data from the snow survey network at different elevations. The climatological data base was judged to be adequate overall on the basis of the level of consistency that was achieved between the snowpack accumulation and streamflow records and the model results.

Climatological data evaluation from the calibration period was undertaken for those climatological stations having the longest records. The same long-term records were statistically analyzed to develop seasonal extreme temperature envelopes. These envelopes of daily maximum and minimum temperatures were later used with the UBC Watershed Model calibrations for the 12 sub-basins in the Columbia River basin to assess probable maximum snowmelt conditions. The long-term summer precipitation records from May through October were also analysed by Storr and Harry, meteorological consultants, who identified the 14 most severe basin rainstorms. They established the synoptic development of each storm, and other meteorological variables contributing to the observed characteristics of each storm. They derived the Probable Maximum Rain (PMR) event using standard hydrometeorlogical procedures for maximizing moisture flows and the efficiency of the atmospheric process in inducing rainfall, and they showed the seasonal difference which could be expected in the probable maximum rainfall amounts.

The work of Storr and Harry, discussed more fully in Section 4.4, provided rainfall estimates over a three-day probable maximum storm over the Columbia River basin, and also estimated the rainfall isohyetal pattern for the event. Their tabulated data also gave daily temperatures during a transition period between conditions of maximum basin-wide snowmelt and the onset of the rainstorm.

3.5 REVIEW AND USE OF SNOW SURVEY DATA

The snow survey data network in the region provides a more comprehensive basis than the temperature and precipitation data network for establishing the precipitation patterns in the mountains in the winter months. The snow survey records for the Columbia River basin in Canada and the United States of America have been collected for about 40 years, and have in recent years been routinely used each year as the basis for forecasting seasonal runoff volumes. Most of the courses have been established in the major runoff producing areas at elevations within 300 m of the tree lines. Other courses have been sited from valley floor elevations to just below glacier elevations and they show within the local areas the variability in the snowpack accumulation pattern over the range of elevation covered.

Snowcourse data is used to indicate percentage departures from average conditions, using the tendency for snowcourses in a local area, and in a given elevation range, to exhibit similar statistical departures each year from long-term averages. The ability of a given set of snowcourses to be quantitively representative of average snowpack accumulations in a given area was examined in the detailed hydrological studies. Using the UBC Watershed Model, consistent relationships were established between seasonal snowcourse readings and the estimates of water equivalent computed by the model. Model estimates and snowcourse data throughout each watershed elevation range (where data were available) were compared on the various survey dates through the snowpack accumulation and depletion period (snow surveys are generally taken monthly or semi-monthly from the beginning of January to the middle of June).

The snow survey data coverage was sufficient to establish reliable basin-wide estimates of the elevation distribution of the water equivalent of the snowpacks throughout the accumulation and depletion periods from 1970 through 1977. In some years, deviation from the more usual pattern was interpeted to result from an unusual pattern of snow accumulation caused by storms from directions other than the prevailing westerly direction. The very large winter snowpack accumulations over the winters of 1971-72 and 1973-74 resulted from frequent passage of intense winter storms embedded in the prevailing westerly flows. These snowpacks, and the seasonal runoff volumes in the sub-basins, were the greatest, or close to the greatest on record.

The 1972 and 1974 snow accumulation patterns were used with 1000-year return period indices of the water equivalent of the snowcourses to establish the severe levels of snowpack accumulation for the Probable Maximum Flood analyses.

3.6 THE UBC WATERSHED MODEL

The UBC Watershed Model[4,5] is a mathematical representation of the land phase (as opposed to the channel phase) of the runoff process. Moisture entering the system is allocated to various forms of storage and eventually leaves the system either as evapotranspiration or as streamflow. A simplified schematic of the UBC Watershed Model is shown in Fig. 3-2.

The key to the operation of the model is the sub-division of the basin into homogeneous elevation band areas. A mountainous drainage basin readily lends itself to such sub-division into sub-areas defined by their elevation range because most of the climatological and hydrological factors vary with elevation. All water balance calculations are based on distributed temperature and precipitation input quantities and are computed on a unit area basis at the mid-elevation of each band. The daily budget changes for each elevation band are converted to volume estimates and summed to obtain the net effect across the basin. This computational procedure allows the model to determine the daily elevation of the snowline throughout the basin and to account for variation of the snow covered area and the snowmelt runoff potential.

Rules governing the allocation of water to actual evapotranspiration loss and to the surface, interflow and groundwater components of runoff are provided in the form of calibration parameters. The model is so constructed that small amounts of rain and snowmelt input contribute principally to groundwater, whereas larger rain and snowmelt inputs contribute larger proportions to surface runoff and interflow. The model therefore produces a realistically sluggish response during low intensity runoff conditions and a faster, more steeply rising hydrograph response during periods of high runoff. Such non-linear behavior of the model is essential for realistic modelling of a range of runoff conditions and for extending the use of the calibration model to extreme events outside the range of calibration data.

After specifying initial parameter values, the allocation of rain and snowmelt to soil moisture and groundwater is functionally determined by the model. The future soil moisture and groundwater recharge levels through time are generated as a result of calibration, and after the first year of analysis, are independent of initial values. On an annual and multi-year basis, this continuous calculation of distributed meteorlogical inputs and the resulting runoff, with no re-initialisation of the model, provides a good evaluation of the calibration because any error in the calibration is detected by a cumulative error, or drift, in the watershed response and is readily recognized. To judge the adequacy of the calibration of the UBC Watershed Model, the computed and measured daily streamflows were compared graphically and statistically over the total calibration period.

3.7 THE UBC FLOW MODEL

The UBC Flow Model[6] accounts for the hydraulic and storage characteristics of the stream channels, natural lakes and reservoirs, and can represent the total network of a complex river system. It accepts the inputs to streamflow generated by the UBC Watershed Model for each basin, and routes these flows to downstream points. The routing method allows travel time influences and storage changes to be functionally dependent upon rates of streamflow, and calibration is achieved using hydrometric measurements obtained at streamflow measurement locations. Reservoir routing changes are determined from elevation based characteristics of the reservoir spillway, outlet structures and turbine facilities, and from stage-storage characteristics of the reservoir.

3.8 UBC WATERSHED MODEL CALIBRATION

The most important aspect of the calibration of the UBC Watershed Model is the correct representation of the cumulative volumes and hydrograph shape factors among the various sub-basins. For extreme floods, the initial abstractions related to the watershed priming process, including snowpack priming, are less important than for small floods and mainly affect the time distribution of runoff in the early summer.

The aim of the parameter calibration was to remove, as far as possible, systematic errors in the reconstitution of seasonal runoff hydrographs. The final calibration results presented in Figs. 3-3 to 3-10 show the recorded and computed simultaneous runoff production in all sub-basins upstream of the Murphy Creek project site. For each year from 1970 through 1977 the figures show the recorded and computed runoff pattern before it was affected either by river channel translation, natural lake regulation or reservoir project regulation. The figures also show for comparative purposes the actual streamflows that were recorded at Trail each year. The graphs of simultaneous basin-wide runoff production above Trail are not the same as the natural streamflow hydrographs that would have been recorded at Trail without the Columbia River Treaty projects. Estimates of natural flows and flows regulated by upstream flood control projects are however derived from the same basin-wide pattern of runoff production in the mountain source areas because these are above the elevation of the reservoirs.

The wide range of flood events from 1970 to 1977 is illustrated in Fig. 3-11 which shows the unregulated peak and volume characteristics of the annual floods at Trail from 1913 to 1977. The flood data coverage in the 1970 to 1977 period is also indicated by Fig. 3-12 which shows the unregulated peaks and volumes of the floods at The Dalles from 1879 to 1977. The final calibration results were developed from flood data during the 1970 to 1977 period that produced record volumes and that would have produced record flows throughout the Columbia River basin of flood levels comparable in magnitude to the most extreme that have occurred since streamflow records commenced at Trail in 1913.

Although longer calibration periods were used for some sub-basins, the final results for the common 1970 through 1977 calibration period are summarized in Tables 3-1 to 3-4. The results presented in the tables are those that can be achieved with hindsight using the summer temperature and precipitation data that were actually observed in each of the years 1970 through 1977. Table 3-1 compares the average recorded and computed seasonal flows. Average April-July, April-August, April-September and annual flow contributions for the eleven major sub-basins are shown in the table. Table 3-2 shows the monthly data, instead of the seasonal data. In both cases, the computed flows show very close agreement with the reference data, and very little discrepancy can be detected.

More detail for each year's April-August runoff production in each sub-basin is given in Table 3-3. Normal operating practice for the regulation of Columbia Treaty projects is to develop April-August runoff volume forecasts for the year and to use them as the primary input for computer simulation of the control plan. The aggregate April-August runoff inflows to the major reservoir storage projects are shown in Table 3-4.

The tabulated calibration results and graphs of basin-wide runoff production throughout the river basin show that good agreement between recorded and reconstituted flows was achieved. The results show in detail the various runoff contributions throughout the basin, and confirm that the volume, peak and shape of the hydrographs were replicated to a high degree at all streamflow measurement locations in the basin. The calibrations were subsequently used to produce reservoir inflow forecasts for all Columbia Treaty projects and to determine the extreme flood hydrographs resulting from Probable Maximum Flood conditions. UBC Watershed Model parameter specifications for each sub-basin, and other details pertaining to the use of data, are given in Appendix B.

TABLE 3-1

UBC WATERSHED MODEL CALIBRATION
AVERAGE SEASONAL RUNOFF, 1970 - 1977

	Average Measured Runoff; Average Computed Runoff; Average Difference between Recorded and Computed Runoff											
Sub-basin	April-July 4 months (m^3/s)			April-August 5 months (m^3/s)			April-September 6 months (m^3/s)			April-March 12 months (m^3/s)		
Donald	316	318	23	322	328	23	296	301	19	171	173	8
Mica local	720	740	42	751	770	41	698	714	28	406	413	14
Revelstoke local	452	431	28	432	416	20	393	379	17	232	222	10
Upper Arrow local	651	652	33	615	609	31	554	550	22	330	326	13
Lower Arrow local	87	85	8	75	73	7	66	64	6	42	38	3
Fort Steele	376	383	23	341	344	21	306	306	19	186	188	9
Libby local	213	324	35	272	283	29	240	251	24	167	165	10
Porthill local	308	299	32	253	251	26	216	217	22	152	142	34
Duncan	192	190	11	190	190	9	173	173	7	103	103	5
Kootenay Lake local	523	521	39	459	453	37	402	395	33	247	242	16
Slocan	200	197	15	177	175	12	156	153	10	96	95	5
Birchbank*1 local	-	38	-	-	32	-	-	28	-	-	16	-

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*1 Reference flows for the Birchbank sub-basin are unreliable. Computed sub-basin flows are given; these are based on the physical description of the Birchbank watershed, and calibrated model parameters for the adjacent lower Arrow sub-basin.

TABLE 3-2

UBC WATERSHED MODEL CALIBRATION
AVERAGE MONTHLY RUNOFF, 1970 - 1977

Average Measured Runoff; Average Computed Runoff; Average Difference between Recorded and Computed Runoff

Sub-basin	April (m³/s)			May (m³/s)			June (m³/s)			July (m³/s)			August (m³/s)			September (m³/s)		
Donald	57	42	15	215	211	31	507	515	33	484	488	43	344	367	38	167	175	26
Mica local	138	133	36	541	539	56	1128	1164	61	1069	1120	91	872	884	65	426	433	50
Revestoke local	108	85	24	419	392	37	717	710	43	562	535	46	352	358	32	197	192	21
Upper Arrow local	153	160	39	665	651	72	1029	1051	64	751	743	78	471	439	62	242	247	35
Lower Arrow local	33	25	9	133	127	18	137	137	15	44	50	7	28	25	4	20	20	2
Fort Steele	64	53	12	340	333	40	691	692	81	410	453	65	204	188	35	123	114	27
Libby local	129	132	33	426	450	43	487	481	59	207	232	42	111	122	21	78	88	10
Porthill local	203	193	58	527	521	40	383	361	37	120	119	27	37	61	24	28	47	21
Duncan	41	43	5	162	167	25	297	302	20	266	260	23	184	187	16	87	90	11
Kootenay Lake	155	160	15	581	565	77	880	864	88	476	502	75	209	184	46	111	93	29
Slocan	53	57	7	207	200	21	336	330	40	202	201	23	86	87	14	50	43	10
Birchbank[*1] local	-	11	-	-	62	-	-	60	-	-	19	-	-	9	-	-	8	-

[*1] Reference flows for the Birchbank sub-basin are unreliable. Computed sub-basin flows are given; these are based on the physical description of the Birchbank watershed, and calibrated model parameters for the adjacent lower Arrow sub-basin.

TABLE 3-3

UBC WATERSHED MODEL CALIBRATION
SUB-BASIN RUNOFF FOR EACH YEAR, 1970 - 1977

Sub-basin	Average April - August Runoff; Computed Percentage Runoff; Percentage of Variance of Daily Flows Explained																							
	1970 (m^3/s)			1971 (m^3/s)			1972 (m^3/s)			1973 (m^3/s)			1974 (m^3/s)			1975 (m^3/s)			1976 (m^3/s)			1977 (m^3/s)		
Donald	267	114	90	336	101	96	434	103	96	272	102	93	366	101	98	262	113	82	397	83	85	239	109	76
Mica local	691	103	94	789	103	91	929	109	86	599	106	87	788	103	75	694	108	71	860	93	90	659	96	84
Revelstoke local	330	102	84	412	102	88	562	100	91	382	91	84	502	93	86	426	99	93	483	94	78	358	92	81
Upper Arrow local	501	98	90	649	92	85	792	103	84	479	102	87	702	98	86	546	112	85	747	91	83	500	99	76
Lower Arrow local	49	101	92	93	84	83	97	97	91	53	113	89	95	91	92	64	114	90	96	88	76	50	105	84
Fort Steele	230	99	87	394	103	83	477	91	89	277	98	88	452	99	94	294	127	43	398	99	72	209	91	80
Libby local	201	90	78	347	94	79	351	106	76	191	118	68	410	92	89	264	120	78	293	107	69	117	127	8
Porthill local	225	120	83	277	87	82	296	92	91	173	118	76	378	93	87	312	109	95	256	92	79	88	103	84
Duncan	166	98	92	203	92	86	235	104	86	158	104	92	212	101	88	167	111	81	225	92	88	155	101	12
Kootenay Lake local	338	85	91	553	105	88	596	99	93	325	101	93	616	95	95	414	124	68	561	94	87	273	85	59
Slocan	125	86	91	217	97	87	231	98	96	128	103	87	227	100	96	157	122	74	214	95	90	115	86	76
Birchbank[*1] local	21	100	-	35	100	-	42	100	-	26	100	-	38	100	-	32	100	-	38	100	-	2.5	100	-

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[*1] Reference flows for the Birchbank sub-basin are unreliable. Computed sub-basin flows are given; these are based on the physical description of the Birchbank watershed, and calibrated model parameters for the adjacent lower Arrow sub-basin.

TABLE 3-4

UBC WATERSHED MODEL CALIBRATION
AGGREGATE RUNOFF FOR EACH YEAR, 1970 - 1977

Average April - August Runoff; Computed Percentage Runoff; Percentage of Variance of Daily Flows Explained

	Columbia River Main Stem						Kootenay River								
Year	Mica Dam (m^3/s)			Columbia River above Castlegar (m^3/s)			Libby Dam (m^3/s)			Kootenay River at outlet of Kootenay Lake (m^3/s)			Columbia River above Trail (m^3/s)		
1970	945	106	95	1838	103	96	432	95	91	1123	97	95	3085	100	97
1971	1126	102	94	2279	98	96	741	99	86	1813	98	90	4309	98	95
1972	1363	107	92	2815	104	94	827	97	94	1980	98	97	5026	101	96
1973	872	104	91	1786	101	95	470	106	88	1098	106	93	3012	103	96
1974	1154	102	86	2453	99	91	861	96	94	2094	96	95	4774	98	95
1975	956	109	76	1993	108	87	558	124	68	1426	119	80	3576	113	89
1976	1257	90	91	2583	91	90	692	102	73	1756	96	86	4553	93	90
1977	898	99	87	1809	98	88	326	104	72	839	97	80	2763	97	89

SECTION 4.0 - DERIVATION OF THE PROBABLE MAXIMUM FLOOD

4.1 GENERAL

Extreme flood estimates of the peak discharge, volume and hydrograph shape in the Columbia River basin upstream of the Murphy Creek project were evaluated by setting up a deterministic computer model of the river system, and by examining the compounding effect of selecting hydrological and climatological inputs at extreme values determined from probability and hydrometeorological analyses. The UBC Watershed Model calibrations provided the basis for extrapolating the runoff response characteristics from situations experienced in the period of record to those that might prevail during the extreme Probable Maximum Flood conditions; the UBC Flow Model provided the framework for representing the effects of flood regulation according to the provisions of the Columbia River Treaty.

Comprehensive analysis of the data base in the Columbia River basin showed that the factors which produce the greatest runoff are the snowpack, the temperature sequence during the melt period and a severe summer rainstorm during the melt period. A combination of these factors was selected which would produce a runoff response of sufficient magnitude to be termed the Probable Maximum Flood (PMF).

The PMF was found to result from the occurrence of the Probable Maximum Rain (PMR) storm at a critical time following the peak of the probable maximum snowmelt flood. The rain for the PMR storm was determined in a separate hydrometeorological study of summer rainstorms. The snowmelt prior to the PMR event was produced by the joint occurrence of extremely high winter snowpacks and extremely high summer temperatures. The conditions that maximized the aggregate snowmelt production and the volume and distribution of the probable maximum snowmelt flood, resulted from the most severe combination of a one in 1000-year return period snowpack accumulation by 1 April and a one in 1000-year return period summer temperature sequence. The one in 1000-year temperature sequence was designed to build over a period of 30 days and culminated in temperatures that produced maximum snowmelt rates over the snow-covered area.

The severe (one in 1000-year) snowpacks provided high snowmelt runoff potential by 1 April and led to extremely high areas of snow cover during the severe temperature sequence. The extended temperature sequence ensured that most of the accumulated snowpack volume was depleted during the summer. The levels of basin-wide snowpack accumulation and the levels of sustained high temperatures in the summer, corresponding to the one in 1000-year return period level, were assigned by the normal probability distribution fit of the observed basin data.

Because of the effect of multiple reservoir developments upstream of the proposed Murphy Creek project site and the resulting modifications to the flood hydrographs in the basin, Probable Maximum Flood hydrographs and the runoff conditions which lead to maximum discharges under natural and regulated conditions are not the same. The level of the input factors remains the same but the sequence of runoff-producing events which maximizes the discharge is different. A number of extreme flood hydrographs were developed and on the basis of the resulting peak flow conditions at the Murphy Creek project, two of these were separately identified as the Probable Maximum Unregulated Flood (PMUF) for the Columbia River at Trail and the Probable Maximum Regulated Flood (PMRF) for the Murphy Creek project. Separate parameter specifications for the UBC Flow Model were used to represent the river flow network relationships in the derivation of the PMUF and to represent the storage and hydraulic conveyance characteristics of the flood control projects in the derivation of the PMRF.

The regulated peak flow conditions at the project site are influenced in varying degrees by the peak, volume and shape features of the hydrographs in the different parts of the basin; the downstream basin location of the project flood hydrographs also reflect the use of volume forecasts and the execution of a flood control plan. In the present study, the framework for determining reservoir releases is given by the 1972 Columbia River Treaty Flood Control Operating Plan and the runoff forecasts required by this plan were developed with the UBC Watershed Model.

4.2 DERIVATION OF ONE IN 1000-YEAR SNOWPACKS

Part of the calibration process involved comparison between snowpacks generated by the UBC Watershed Model and snowcourse observations. Observations from different courses exhibit systematic differences in the levels of snowpack accumulation, even when the data is obtained from the same elevation in the basin, and, as a result of this, the elevation distribution of the snow wedges in each sub-basin is indicated only approximately by the snow survey data. The final calibrations, showing the best streamflow reconstitution, led to an improved understanding of the seasonal pattern of snowpack accumulation and depletion, and identified the snow courses which consistently provided good estimates of elevation dependent snow cover.

A frequency analysis was made on the observed 1 April water content of the snowpacks for all locations having a period of record of at least 12 years. The one in 1000-year snowpack at each elevation within each sub-basin was estimated by extrapolating the frequency curves for the individual snow courses which are at specific elevations. Curves representing the 1000-year return period snowpack versus elevation relationship were drawn through the 1000-year return period points using the shapes of the curves obtained in the calibration of the years of highest snowpack accumulation - 1974, 1972 and 1967. Estimates of the basin snowpack water equivalent at the mid-elevation of the zones represented in the UBC Watershed Model calibrations were taken from these sub-basin curves.

The disposition of the severe (one in 1000-year) snowpack across the basin affects the hydrograph pattern at the Murphy Creek project in a complex way. Since maximum snowmelt rates in the basin rarely exceed 70 mm in one day at any time during the snowmelt period, areas of snow cover, rather than the depths of snow cover, are more important to the production of peak river discharges from snowmelt. The area of snow cover in mountain areas is largely governed by a snowline elevation. Thus, the peak snowmelt runoff potential through the summer is determined, amongst other factors, by the elevation of the receding snowlines. For the severe 1 April snowpack conditions, snowlines in the Revelstoke, Mica reservoir, upper Arrow and Duncan watersheds were found at approximately 900 m by early June and between 1500 and 1800 m by the end of July. The snow-covered area corresponding to these snowline elevations varies from 80 to 90 percent of the sub-basin area in early June to between 30 and 50 percent by the end of July. In these watersheds, the total runoff potential resulting from the snow cover remains close to the maximum possible levels until early June because of the very large depths of snow.

For the severe 1 April snowpacks in the East Kootenay region, snowlines were found to recede to the 1500 m elevation range by early June and to between 2100 and 2400 m by the end of July. The snow-covered area in these drier parts of the basin fell from 50 percent of the watershed area in early June to less than 20 percent by the end of July. These more pronounced levels of snowline recession were associated with more dramatic seasonal reductions in the snowmelt runoff potential than would be experienced in the upper Columbia regions of the basin.

Because of the steep gradient of snow depth with elevation through the lower valley slopes the volume of runoff contributed from the lowest

600 m of elevation range is small relative to the volume of seasonal runoff which would result from the severe (one in 1000-year) snowpack in mountain areas. The severe mountain snowpacks were approximately 1.7 times the April 1 average water equivalent in the north and 1.9 times this average in the south. The sub-basin volume runoff contributions from these snowpacks reflect these differences.

4.3 DERIVATION OF ONE IN 1000-YEAR TEMPERATURE SEQUENCES

The snowmelt formulation incorporated in the UBC Watershed Model is based upon the use of daily temperatures and can be readily used in areas where other data such as solar radiation, wind speed and dewpoint temperatures are not available. Melt components are defined in terms of maximum, mean and minimum daily temperature and influences related to other types of data, such as radiation data, are indirectly built into the snowmelt formulation.

Extreme snowmelt runoff events were estimated by computing the snowmelt that would result from extremely warm temperatures occurring during the snowmelt period. The temperature sequences developed for the derivation of the probable maximum snowmelt floods were based upon a statistical analysis of daily maximum and mean temperatures recorded at each of the meteorological stations used to compute sub-basin snowmelt in the model calibrations. The maximum and mean temperature sequences for the estimation of extreme snowmelt conditions were constructed so that when stacked in ascending order, the cumulative 1, 2, 3, 5, 10, 15 and 30-day temperatures each had a return period of 1000 years. This analysis was carried out for selected time periods starting 16 April, 1 May, 16 May, 1 June, 16 June and 27 June. In addition, a severe (one in 1000-year) temperature sequence starting 7 July was derived. The cumulative temperatures were estimated from up to 80 years of data by extrapolations based on the normal distribution.

The peak, volume and shape of the extreme snowmelt floods, though primarily determined by the high temperature sequence, are also affected by the weather conditions occurring during the melt season before and after the extreme snowmelt sequence. The seasonal runoff response was therefore examined with different possible background weather patterns to determine those conditions that would produce the highest flood levels. The background conditions that were tested were abnormal for the time of year at which they occurred and were selected from weather sequences observed during the calibration period. The background weather patterns included seasonal data from a very warm summer (1970), a very cool spring with heavy mid-summer rains (1972) and a very cool and wet summer with heavy summer rainfall runoff (1976). The impact of the background weather was to cause additions of up to 10 to 15 percent in the April-August runoff volume.

4.4 DERIVATION OF THE PROBABLE MAXIMUM RAIN (PMR)

In addition to heavy snowpack and high temperature conditions, the third factor leading to Probable Maximum Flood conditions at the Murphy Creek project site is a major rainstorm event. All meteorological input sequences for maximum flood estimation incorporated a PMR event at a critical time during the runoff. The seasonal variation of probable maximum rainfall was determined by Storr and Harry, meteorological consultants. The greatest rainfall potential normally occurs in June and coincides with the period of high runoff from snowmelt.

It is not realistic to assume that heavy rainfall will coincide with extreme high temperatures and the PMR event was therefore assumed to occur 3 days after maximum snowmelt conditions, following a 2-day transition period during which cooling would take place. Compared to snowmelt, major rainfall inputs have additional significance because they cannot be forecasted.

The characteristics of the PMR storm were derived by using standard hydrometeorlogical procedures for maximizing the parameters of the most severe storm that has occurred within the general vicinity of the project drainage area. (This storm occurred between 28 June and 30 June 1935.) The PMR event was greater in scale and intensity than the historical storm and was transposed and centred on the Arrow Lakes drainage area. This positioning of the storm is a severe assumption because of the closeness to the project site and because of the quick runoff response to the high intensity rainfall in a highly primed watershed. In the case of the Probable Maximum Regulated Flood (PMRF), the timing was even more critical because reservoir flood control capability in the Mica and Arrow Lakes reservoirs was no longer available at the time of the rainfall event.

Over a 3-day period, the Probable Maximum Rain would provide a variable depth from over 180 mm in the centre of the storm to lesser amounts on adjacent areas in the Columbia River basin. The high dewpoint temperatures during the storm ensured that virtually all of the precipitation falling in the basin occurred as rain. Two analyses for determining the rainfall inputs were considered. In the first analysis, the isohyetal areas of the PMR storm were taken from Fig. 26 of the Storr and Harry report and the sub-basin rainfall quantities were derived directly from the estimated isohyetal pattern. The isohyetal pattern of the PMR is reproduced as Fig. 4-1. In the second analysis, the scale of the storm was determined by the UBC Watershed Model using the calibrated parameters for summer rainfall distribution, and the meteorological station inputs given in Table 12 of the same report. These inputs are reproduced in Table 4-1. The second analysis corresponded more closely with the 1965 through 1978 historical relationships between summer storm inputs and the resulting runoff patterns.

The PMR inputs used in the derivation of the Probable Maximum Floods were conservatively based on the analysis that produced the most severe basin-wide rainfall inputs. The areas of the storm isohyets for the two analyses are given in Table 4-2. In the Columbia River drainage area including the Mica reservoir, Revelstoke, upper Arrow and Duncan watersheds the rainfall inputs for the sub-basins calibrated on Glacier meteorological station precipitation were greater when point source data based on Table 12 of the Storr and Harry report were used. In the Kootenay River drainage area the PMR inputs were based on the isohyetal pattern given in Fig. 26 of the Storr and Harry report rather than the point source data. Because of the particular spatial characteristics of the maximized storm, the rainfall inputs in the Kootenay River basin are far less significant than those occurring along the Columbia River mainstem although the Slocan valley and Kootenay Lake region contributions do have some effect on the downstream flood peak.

4.5 DERIVATION OF THE PROBABLE MAXIMUM UNREGULATED FLOOD (PMUF)

The PMUF was derived to illustrate the peak runoff potential of the basin compared to historical events and to provide a basis for demonstrating the importance of reservoir operations under the Columbia River Treaty. For the PMUF, the extreme meteorological sequences discussed above were used. As shown in Table 4-3, the maximum discharge at the project site was produced by a 30-day high temperature sequence starting 1 May followed by the PMR event. The peak daily flows were the same using background weather (weather before and after the PMUF event) from both 1970 and 1972 but the maximum April-August volume was higher with 1972 weather conditions. The flood generated with the 1972 data has a peak flow of 19 900 m^3/s and an April-August volume of 95 x $10^9 m^3$. This is the Probable Maximum Unregulated Flood (PMUF), that is, the flood that would be experienced, in the absence of the regulation provided by the Columbia River Treaty reservoirs.

Earlier high temperature sequences showed peak runoff capability 2 weeks ahead of the PMUF to be 16 400 m^3/s and to fall to 12 900 m^3/s by the end of July. The seasonal April-August volume for the extreme flood producing sequences ranged from 86 x 10^9 to 95 x $10^9 m^3$.

4.6 DERIVATION OF THE PROBABLE MAXIMUM REGULATED FLOOD (PMRF)

(a) General Criteria for Treaty Project Operations

The Columbia River Treaty requires that reservoirs constructed in Canada be operated according to specified flood control and hydroelectric operating plans. The Protocol to the Treaty provides further clarification of the principles and detailed requirements of the Treaty.

The general criteria for power operations are established in the Principles and Procedures for the Preparation and Use of Hydroelectric Operating Plans (May 1979).[7] Annex A of the Treaty (Principles of Operation) provides for the development of hydroelectric operating plans 5 years in advance to furnish the Treaty Entities with an Assured Operating Plan for Canadian storage. In addition, the Treaty provides that a Detailed Operating Plan may be developed immediately prior to each operating year to produce more advantageous results through the use of updated estimates of loads and resources. In most years, implementation of the Detailed Operating Plan ensures sufficient peak flow reduction for there to be little or no flood damage risk along the main stem of the Columbia River downstream of the Treaty projects.

Whenever seasonal forecasts of the unregulated flood volume at The Dalles exceed 148 x $10^9 m^3$ (approximately 130 percent of the long-term average), additional non-Treaty storage may be required to control these large floods. Under such circumstances the Detailed Operating Plan may be revised, and subject to the conditions provided by the Treaty, each Treaty project may be operated as part of a centralized plan for basin wide flood control. The general criteria for major flood control operations are established in the Columbia River Treaty Flood Control Operating Plan (October 1972).[8] Annex A of the Treaty stipulates that the United States Entity will submit flood control operating plans and that the Canadian Entity will operate in accordance with the plan's flood control storage diagrams or any variation which the Entities agree will not be adverse to the desired aim of the flood control plan. The extreme flood conditions analyzed in this report (Volume 1) would all require regulation according to the Columbia River Flood Control Operating Plan.

(b) Principles of Flood Control Regulation

The procedures followed for operating the Columbia River Treaty projects (Mica, Arrow, Duncan and Libby) are described in the Columbia River Treaty Flood Control Operating Plan, dated October 1972. Under this plan, the normal designated storage space at each project is held vacant until storing for flood control or refill starts, unless involuntary storage occurs.

The basic objective of the flood control operation is to regulate flood runoff to non-damaging levels, if possible, and to regulate larger floods to the lowest possible level with the available flood control space. The Columbia River at The Dalles, Oregon, is used as the main control point; an Initial Controlled Flow at The Dalles is established on the basis of seasonal runoff volume forecasts and flow releases from the upstream reservoir operations are scheduled to meet this controlled flow objective. It is generally assumed that efforts to meet the flood control objective at The Dalles will result in adequate flood control throughout the basin. There are other areas in the basin where flooding can occur and separate flood control objectives for these local areas are recognized as part of the overall flood control plan. For example, at Revelstoke, flows should not exceed 5660 m³/s when Arrow reservoir reaches its full operating level, El. 440.7; damage begins at Trail when flows exceed 6370 m³/s and major flood damage will occur when flows reach 7930 m³/s; at Nelson, B.C., major damage begins when Kootenay Lake reaches El. 536.1 and at Bonners Ferry, Idaho, flooding will occur when flow levels exceed 1610 m³/s. (These local upstream conditions could occur in a year when flood control measures in other parts of the basin lead to effective flood control at The Dalles.)

The four treaty reservoirs upstream of the Murphy Creek project site are all operated primarily for flood control in the lower Columbia River. There are two categories for these reservoirs determined by the way in which releases are made. Mica, Duncan and Libby belong to the category that is operated with fixed releases. For these reservoirs, storage space is assigned on 1 April and subsequent releases are based on the forecast of runoff volume at the reservoir. Arrow reservoir is in a different category. It is operated with variable releases with reservoir storage space provided by 1 April on the basis of runoff forecasts at The Dalles. For the first category, forecasts at the reservoirs govern releases; for the second category, forecasts at The Dalles govern releases.

If the flooding risk at The Dalles were sufficiently high and it appeared that peak discharges at The Dalles in excess of 17 000 m³/s would occur, additional storage space in Mica reservoir below El. 730.9 may be drafted to specifically alleviate the risk of flooding in the lower Columbia River. This provision is provided in the flood control plan, but it is expected that the need for such "On Call" storage would arise very infrequently. The

Mica reservoir flood control space below El. 730.9 could be used to meet Canadian flood control objectives at Trail or Revelstoke, but the Mica reservoir project was not specifically designed for this purpose. The additional 6.2 x 10^9m^3 of non-Treaty storage between El. 707.1 and 730.9 was provided to allow drafting of the Mica reservoir under extremely low streamflow conditions to augment power production at Mica, Revelstoke and other downstream power plants in the U.S.A.

According to the 1972 Columbia River Treaty Flood Control Operating Plan, the date when storage for downstream flood control begins should be related to the date when the flows at The Dalles are forecasted to reach the Initial Controlled Level. For Duncan and Libby, storage for flood control starts 15 days in advance of that day; for Arrow, flood control begins just 2 days in advance. The beginning of the Mica flood control operation is determined by the United States Entity. For the present study, it was assumed that Mica storage operation would begin 7 days in advance of the date for the Initial Controlled Flow at The Dalles. This assumption was recommended by the Manager, Canadian Entity Services.

The Columbia River Treaty (Paragraph 3, Annex A, Principles of Operation) further requires that the discharge capacity provided for flood control operations be evaluated on the basis of the full use of any conduits provided for that purpose plus one half of the hydraulic capacity of the turbine installation at the time of commencement of the operation of storage under the Treaty. The regulation analyses reported herein were based upon the assumption that all of the turbine units at the Libby and Mica projects could be used. The final results of the PMRF analysis, and the upstream Treaty project release schedules, were checked against the above release limitation at the power plants. Conditions that might have required the discharge capacity of the additional turbine units were not experienced, except in April and early May when the reservoir levels were at their minimum levels prior to the refill of reservoir storage. During the major refill period from mid-May to July, the release schedules were found to be compatible with the regulation requirements of the Columbia River Treaty.

(c) Evacuation of Reservoir Storage

The storage space to be provided in the treaty reservoirs by 1 April of each year is based on runoff forecasts for the respective projects, except in the case of Arrow reservoir, where the storage evacuation is based upon the runoff forecast for The Dalles, Oregon. The storage levels are calculated from either flood control or assured refill considerations, depending on the potential flood risk indicated by the forecast.

For the present study, the runoff forecasts for each of the treaty projects and for the Columbia River at Trail were simulated using an initial condition of one in 1000-year 1 April snowpacks, and the historical temperature and precipitation data from the period 1965 through 1977. The storage that would be required in each of the reservoirs for flood control was determined from the mean forecasted April-August runoff volume. However, for the assured refill calculations, the 95 percent lower confidence limit on the forecasted April-July runoff volume was used (as required by the plan). The simulated runoff forecast results and the associated reservoir storage levels are given in Table 4-4.

The 1 April level for Mica reservoir was selected to meet assured refill criteria (as recommended by Generation Planning BCH). Thus, even though the flood risk indicated by the snowpack runoff potential would have, according to the 1972 operating plan, permitted drawdown of the Mica reservoir to El. 714.7, a level of 8 m higher was used to conservatively account for power production objectives. The other Columbia Treaty reservoir operations were assumed to follow the normal practice of full reservoir drawdown by 1 April. During April and May, the reservoirs are all operated to maintain 1 April levels unless there is involuntary storage.

With a PMF event imminent in Canada, it is likely that the U.S. Entity would request the use of On-Call storage at Mica, and that the 1972 Columbia River Flood Control Operating Plan would be implemented. This is likely because with a April-August flood volume forecast at Trail of 85 x $10^9 m^3$ the expected April-August volume forecast at The Dalles would be about 222 x $10^9 m^3$. This flood volume is 50 percent higher than the 148 x $10^9 m^3$ volume forecast at The Dalles that is sufficient to require the use of the flood control plan in Treaty reservoir operations. This estimate of the flood volume at The Dalles was obtained by extrapolation of the best-fit linear relationship between historical flood volumes at Trail and at The Dalles shown in Fig. 4-2. Linear extrapolation of Fig. 4-2 indicates that a 85 x $10^9 m^3$ flood volume forecast in Canada would be associated with a flood volume at The Dalles of between 197 x 10^9 and 247 x $10^9 m^3$ as the upper and lower 95 percent confidence limits.

(d) Refill of Reservoir Storage

The Flood Control Operating Plan specifies the required constant outflows from the Mica, Duncan and Libby projects, given the storage space available at the start of the Flood Control Refill Period and the inflow volume forecasts from the starting date of flood control operation to the end of August. For each reservoir the starting date used in the study had a fixed lead time ahead of the Initial Controlled Flow date at The Dalles, and varied with the timing of the high temperature sequences used to generate PMF conditions in Canada. It was assumed that forecasts, when unregulated flows at The Dalles would have exceeded the Initial Controlled Flow, would lead to a starting date of 15 May for maximized temperature sequences ending by that date, and 30 May for the later temperature sequences.

The operation of Arrow reservoir is related directly to the flood control requirements at The Dalles and these were not simulated in this study. It was therefore necessary to be somewhat arbitrary in selecting the releases from Arrow; it was considered reasonable to base Arrow release schedules on local flood control objectives at Trail and to assume that meeting these local flood control needs would not be in conflict with flood control objectives downstream. A summary of the operating considerations during refill is given in Table 4-5.

Libby reservoir releases were scheduled to minimize the flood threat at Bonners Ferry; Kootenay Lake outflows were based on free-flow conditions, that is, the control structure was not used to induce any additional storage above that which would occur naturally with the outflow gates wide open. This is in accordance with the principles of operation governing Kootenay Lake regulation in extreme flood years.

The Mica reservoir releases were also scheduled to complete reservoir refill on 31 July. This normal practice is required under the provisions of the Treaty. This operational requirement was adopted in the development of the Probable Maximum Regulated Flood because it would lead to the most severe "reasonably possible" regulated flood peak at the Murphy Creek project site.

At the present time, there is no assurance that whenever there is a very high retention of snow cover in July in the Mica reservoir basin that the Mica project outflows would be increased above the fixed discharge requirement of 280 m^3/s to enable postponement of refill beyond 31 July. Under the circumstances leading to the extreme conditions that might lead to the Probable Maximum Flood event, it may, however, be possible to postpone the reservoir refill at the Mica project by 2 to 4 weeks without risk to the requirement for assured refill and without jeopardizing the flood protection required throughout the Columbia River basin. It was recognized that the operational strategy adopted in this study of completing refill on 31 July would lead to lost opportunities for regulating flood flows in August.

After the treaty reservoirs had reached their normal full supply levels, inflows were passed and, except where it was inevitable, surcharge in upstream storage reservoirs was not used to reduce PMF peak flows at the Murphy project site.

(e) The Probable Maximum Regulated Flood (PMRF)

The extreme runoff inputs used to simulate regulated flow conditions and to produce the extreme regulated inflow hydrographs to the Murphy Creek project are the same as those producing the unregulated hydrograph peaks shown in Table 4-3. The simulations showed that the maximum flood peak which would be experienced after considerations for the operation of the Treaty reservoirs would occur later than the PMUF and would result from a much lower unregulated peak flood. This is because the treaty reservoirs, operated according to the Columbia River Treaty Flood Control Operating Plan, provide effective flood control for the Murphy Creek project site (near Trail) up until 31 July, the date by which filling of the reservoirs would be completed.

The flood level reduction at the Murphy Creek project site due to upstream storage regulation is shown for the complete flood control period in Figs. 4-3, 4-4 and Appendix C. These figures show for each extreme flood sequence both the unregulated and regulated inflow hydrographs to the Murphy Creek project and the Columbia River streamflow hydrograph that was recorded at Trail in 1948.

(This year produced the most damaging flood levels in the basin since 1894.) The major flood control benefit occurs early in the flood period when the treaty reservoirs are filling and the regulated flow levels to the Murphy project are substantially below unregulated flows.

Before the construction of Keenleyside Dam, the Arrow Lakes retained part of the flood volume during major floods and released a maximum outflow that was usually considerably less than the inflow. Since the dam was built, the level of Arrow Lakes was raised to a maximum of El. 440.7 and this provided an increase in the outlet capacity. With the present regulation under the provisions of the Columbia River Treaty, a large inflow to Arrow Lakes at the normal full pool level would result in an outflow larger than that which would have occurred before the construction of the dam. Under full pool conditions at El. 440.7, there would be a loss of natural regulation benefits, and the regulated flows at Trail would be higher than the unregulated flows which would have induced a natural surcharge on the upper and lower Arrow Lakes.

The peak regulated flows resulting from the extreme flood runoff inputs are summarized in Table 4-6. This table shows that the PMUF with a peak of 19 900 m^3/s and with a maximum April-August runoff volume of 95 x $10^9 m^3$ was reduced to 9460 m^3/s at the Murphy Creek site as a consequence of the regulation provided by the treaty reservoirs. Runoff conditions resulting in higher peak flows at the Murphy Creek site were produced by a (1976) very wet and cool weather sequence from April to early July with a 20-day high temperature sequence starting 7 July followed by the PMR event at a critical time when the regulating capabilities of the upstream reservoirs would not be available.

Under these conditions, the "pass inflow" requirement for the Arrow project reservoir slightly increased the 12 900 m^3/s unregulated peak on 27 July to 13 100 m^3/s on 2 August at the Murphy Creek site. (This is mainly due to the loss of natural regulation benefits in the Arrow Lakes as explained before.) This is the Probable Maximum Regulated Flood (PMRF) which the facilities at the Murphy Creek project site would experience with the Columbia River system operated according to the Flood Control Operating Plan. A summary of reservoir operations for the PMRF is given in Table 4-7. The maximum streamflows and associated reservoir conditions upstream in the basin are shown for all flood control locations and reservoir projects for the PMUF sequence in Figs. 4-5 to 4-12, and for the PMRF sequence in Figs. 4-13 to 4-20. All projects in the basin passed local streamflows contributing to the probable maximum floods above the Murphy Creek projects within their design capabilities. (Details of the flood conditions at the upstream Columbia Treaty projects are given in Appendix C and a further examination of the PMRF flood severity is included in Appendix D.)

The above results were checked against the 50 percent limitation on the hydraulic capacity of the turbine installations covered by the Columbia River Treaty. During the major flood control period and the following flood recession, there were no conflicts between the requirements of the Treaty and the project release schedules adopted in this study. However, when the reservoirs were drawn down to their minimum levels prior to the start of refill operations, the hydraulic capacity of the two additional turbine units at both the Libby and Mica projects were used over a short period in May. This use accounted for a small excess of outflow capability of both projects between 1 May and the starting date of refill operations (15 May for the Libby project and 23 May for the Mica project). Adjustments could have been made to the regulation analyses in the period prior to the start of refill operations, but the adjustments would have been small and would not have led to any change in the results. The same results could be achieved with a slightly lower drawdown at the Mica project by 1 April and by a small adjustment to the daily release schedule at the Libby project following the start of refill operations.

TABLE 4-1

ESTIMATED CLIMATOLOGICAL STATION DATA FOR PMR EVENT

Climatological Station	Maximum Daily Temperature (°C); Minimum Temperature (°C); Rainfall (mm)				
	Day -2	Day -1	Day PMR 1	Day PMR 2	Day PMR 3
Golden	21 10 0	18 13 0	16 13 38	13 10 25	16 10 13
Valemont	24 07 0	24 07 0	21 10 13	18 10 25	18 07 13
Blue River	21 07 0	21 07 0	18 10 25	16 10 50	16 10 13
Glacier	18 04 0	16 07 0	13 10 13	13 10 64	10 07 64
Revelstoke	24 13 0	21 13 0	18 13 38	13 13 76	16 10 25
Lardeau	24 13 0	18 10 0	18 13 13	13 10 50	13 10 38
Kaslo	21 13 0	18 13 0	18 13 13	16 13 38	16 10 25
Canal Flats	24 13 0	21 13 0	18 13 0	18 13 13	13 10 38
Fauquier	21 13 0	18 13 0	18 13 13	13 13 76	13 10 25
Creston	24 13 0	21 13 0	21 13 0	21 13 0	18 10 13
Nelson	24 13 0	21 13 0	21 13 0	16 13 50	13 10 64
Cranbrook	24 10 0	24 13 0	24 13 0	24 13 0	18 13 25

TABLE 4-2

AREAS OF THE PROBABLE MAXIMUM RAINFALL ISOHYETS

Rainfall Isohyet (mm)	Portion of the Columbia River drainage area above Castlegar (km²) Based on Storr & Harry[*1] (Fig. 26)	Portion of the Columbia River drainage area above Castlegar (km²) Based on Storr & Harry (Table 12)	Portion of the Kootenay River drainage area above Murphy Creek Project (km²) Based on Storr & Harry (Fig. 26)	Portion of the Kootenay River drainage area above Murphy Creek Project (km²) Based on Storr & Harry (Table 12)
>180	1 450	6 060	520	100
>150	5 130	18 540	2 330	3 080
>130	9 220	22 220	7 400	3 470
>100	18 600	30 200	10 930	5 540
>80	28 360	32 600	12 660	15 800

[*1] "A Study of Probable Maximum Rainfall for Three Watersheds in Southeastern British Columbia", D. Storr and K.F. Harry: Report submitted to B.C. Hydro and Power Authority for the Murphy Creek Project Probable Maximum Flood Study, January 1980.

TABLE 4-3

UNREGULATED EXTREME FLOODS AT MURPHY CREEK PROJECT SITE

Weather Sequence		Unregulated Peak Daily Discharge (m^3/s)	Date	Runoff April-August Volume ($10^9 m^3$)
72AP16MY16*[1]		16 400	24 May	92.5
72MY01MY31	PMUF*[2]	19 900	8 June	95.0
72MY16JN15		18 000	21 June	93.8
70MY01MY31		20 000	8 June	94.5
76MY01JL27		15 000	2 June	86.0
76MY16JL27		14 800	17 June	89.0
76JN01JL27		14 700	1 July	90.4
76JN16JL16		13 600	16 July	90.0
76JN16JL27		13 700	16 July	90.0
76JN27JL27		12 600	13 July	90.2
76JL07JL27		12 900	27 July	89.2

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*[1] 72AP16MY16
- 72 refers to background weather data for 1972
- AP16 refers to starting date of extreme temperature sequence - 16 April
- MY16 refers to starting date of Probable Maximum Rain event - 16 May

*[2] PMUF - The Probable Maximum Unregulated Flood, i.e. the most severe flood based on peak and volume

TABLE 4-4

RUNOFF VOLUME FORECASTS AND REQUIRED STORAGE LEVELS

					Forecast April-July			
Columbia Treaty Project	Forecast April-August Inflow Volume (10^9m^3)	Chart No.[*1]	On-Call Storage Required (10^9m^3)	Associated Reservoir Level (m)	Inflow Mean (10^9m^3)	Volume 95% Confidence Level (10^9m^3)	Power Discharge Requirement (m^3/s)	Reservoir Level for Assured Refill (m)
Mica	22	8	13	714.7	17	14	280	722.7
Duncan	4	4	2	548.6[*2]	3	2	3	546.9
Libby	15	10	6	697.1	14	12	85	697.1
Arrow	150 (The Dalles[*3])	5	9	420.0	36	31[*4]	140	420.0

[*1] Charts from the Columbia River Treaty Flood Control Operating Plan.

[*2] The On-Call storage and associated reservoir level based on an earlier storage table or Duncan reservoir - revised storage table indicates a storage capacity of 1.7 x 10^9m^3 above the minimum pool level 546.9 m.

[*3] Storage required in Arrow based on runoff volume forecast at The Dalles - Runoff volume at The Dalles estimated as follows:

Forecasted April-August runoff volume for Trail = 85 x 10^9m^3.
Average April-August runoff volume for Trail = 53 x 10^9m^3.
Average April-August runoff volume for The Dalles = 112 x 10^9m^3.
Average April-August runoff volume for the Columbia River below Trail = (112 - 53)10^9 = 59 x 10^9m^3.
Estimated April-August runoff volume for The Dalles assuming the runoff for the Columbia River downstream of Trail is approximately 10 percent above average = 85 x 10^9 + 1.1 x 59 x 10^9 = 150 x 10^9m^3.

[*4] The inflow volume is the total unregulated volume for the Columbia River above Arrow minus the storage available for refill in Mica reservoir.

i.e. 31 x 10^9 - 11 x 10^9 = 20 x 10^9m^3 (11 x 10^9m^3 available for refill at El. 722.7, Mica project).

TABLE 4-5

SUMMARY OF OPERATING CONSIDERATIONS DURING REFILL

Columbia Treaty Project	Starting Date[*1] for Flood Control Refill Period	Remaining Runoff Volume Forecast to 31 August ($10^9 m^3$)	Chart No.[*2]	Specified Project Outflow (m^3/s)	Other Considerations
Mica	8 May	21	9	280	Fill reservoir to El. 754.4 by 31 July. Maintain some storage capability in July by increasing releases, if necessary.
	23 May	20	9	280	
Arrow	13 May	-	-	-	Fill reservoir to El. 440.7 by 31 July. Provide flood control for Castlegar - flooding starts at 6370 m^3/s major flooding occurs at 7930 m^3/s. Restrict rate of increase in outflows to 710 $m^3/s/d$, if possible.
	28 May	-	-	-	
Duncan	30 April	-	-	3	Fill reservoir to El. 576.7 by 31 July. Restrict rate of increase in outflows to 110 $m^3/s/d$, if possible.
	15 May	-	-	3	
Libby	30 April	15	11	910	Fill reservoir to El. 749.5. Provide flood control for Bonners Ferry - flooding starts at 1610 m^3/s. Restrict rate of increase in tailwater level to 1.2 m/d, if possible.
	15 May	14	11	790	

[*1] The starting data has a fixed lead time in advance of the date when unregulated flows at The Dalles would have reached an Initial Controlled Flow (ICF) level. The assumed ICF forecast date for the extreme temperature sequence starting on 16 April was 15 May, 15 days ahead of the ICF forecast date for all later extreme temperature sequences. The lead time required in advance of the ICF forecast date is 15 days for the Duncan and Libby projects, 7 days for the Mica project and 2 days for the Arrow project.

[*2] Charts from the Columbia River Treaty Flood Control Operating Plan.

TABLE 4-6

REGULATED EXTREME FLOODS AT MURPHY CREEK PROJECT SITE

Weather Sequence		Regulated Peak Daily Discharge (m^3/s)	Date	Runoff April-August Volume ($10^9 m^3$)	Unregulated[*1] Peak Daily Discharge (m^3/s)
72AP16MY16[*2]		6 370	17 May-21 July	92.5	(16 400)
72MY01MY31	PMUF[*3]	9 460	14 June	95.0	(19 900)
72MY16JN15		11 100	22 June	93.8	(18 000)
70MY01MY31		9 850	26 June	94.5	(19 900)
76MY01JL27		11 000	3 August	86.0	(15 000)
76MY16JL27		10 700	2 August	89.0	(14 800)
76JN01JL27		10 500	2 August	90.4	(14 700)
76JN16JL16		10 800	22 July	90.0	(13 600)
76JN16JL27		10 500	2 August	90.0	(13 700)
76JN27JL27		12 000	2 August	90.2	(12 600)
76JL07JL27	PMRF[*4]	13 100	2 August	89.2	(12 900)

[*1] From Table 4-3

[*2] 72AP16MY16
- 72 refers to background weather data for 1972
- AP16 refers to starting date of extreme temperature sequence - 16 April
- MY16 refers to starting date of Probable Maximum Rain event - 16 May

[*3] PMUF - The Probable Maximum Unregulated Flood, i.e. the most severe flood based on peak and volume (Section 4.5)

[*4] PMRF - The Probable Maximum Regulated Flood (Section 4.6: Since natural Arrow Lakes regulation is not available, and because of the "pass-inflow" requirement of the reservoir operations, the PMRF peak will exceed the unregulated peak from the same basin runoff.)

TABLE 4-7

TREATY PROJECT AND OPERATIONAL DATA FOR MURPHY CREEK PROJECT PMRF

Reservoir	1 April Level (m)	1 March Volume Forecast (1 April-31 August) ($10^9 m^3$)	Reservoir Operation[*1]		Maximum Reservoir Elevation (m)	Regulated Peak Outflow (m^3/s)
			Period	Releases		
Mica	722.7	22	1 April-23 May	- release inflow	754.4 (31 July)	4 530 (31 July)
			24 May-25 July	- 280 $m^3/s/d$		
			26 July-31 July	- variable outflow specified		
			1 August-	- release inflow		
Revelstoke	-	-	total period	- release inflow	-	6 430 (31 July)
Arrow	420.0	-	1 April-23 May	- freeflow	440.7 (31 July)	9 030 (2 August)
			24 May-27 May	- release inflow		
			28 May-23 July	- 1400 $m^3/s/d$		
			24 July-26 July	- variable outflow specified		
			27 July-	- release inflow (if possible)		
Libby	697.1	15	1 April-27 May	- release inflow	749.5 (28 July)	1 220 (1 August)
			28 April-15 May	- variable outflow specified		
			16 May-20 July	- 760 $m^3/s/d$		
			21 July-24July	- 1400 $m^3/s/d$		
			25 July-	- release inflow		
Duncan	546.9	4	1 April-4 May	- release inflow	577.4 (1 August)	820 (1 August)
			5 May-15 May	- variable flows specified		
			16 May-13 July	- 3 $m^3/s/d$		
			14 July-19 July	- variable flows specified		
			20 July-	- release inflow (if possible)		
Kootenay Lake	529.8	-	total period	- freeflow	536.1 (26 July)	3 500 (26 July)
Murphy Creek			total period	- inflow hydrograph given	-	13 100 (2 August)

[*1] Reservoir Operations are described in the Columbia River Treaty Flood Control Operating Plan, dated October 1972.

Mica, Duncan and Libby reservoirs are operated to a specified release based on the Volume of Runoff Forecast.

Arrow reservoir is operated with variable releases to provide regulation for flows in the lower Columbia River, and at the same time, to provide local flood protection.

Kootenay Lake is operated according to the International Joint Commission Order of Approval dated September 1943. Freeflow conditions must exist above El. 531.95 m.

Revelstoke and Murphy reservoirs are operated as Run-of-River Projects.

SECTION 5.0 - SUMMARY OF FINDINGS

(a) General

1. The high mountain chains rising over 3000 m above sea level in the Murphy Creek Project drainage area provide an elevation barrier to the prevailing weather systems coming from the west and the Pacific Ocean and have a significant influence on the climates of local tributaries (Section 2.1).

2. Weather records have been taken in the basin for about 80 years and show a variation from 380 mm of average annual precipitation in valley bottoms to 1500 mm at the elevation of the highest climatological station; the maximum recorded annual precipitation was approximately 2500 mm at El. 1800 (Section 2.2).

3. Precipitation over a period of record is more variable in the valleys where most of the weather stations are located than in the mountains where most of the runoff originates (Section 2.2).

4. Temperatures over the basin tend to be more uniform than precipitation (Section 2.2).

5. In spring, maximum daily temperatures increase at an average rate of approximately 4°C per month and minimum daily temperatures increase at the rate of 3°C per month (Section 2.2).

6. The potential for the heaviest rainfall exists in June and July and coincides with the period of intense runoff from snowmelt (Section 4.4).

7. The data network, established since the Columbia River Treaty was implemented, provides detailed information on the pattern of snowpack accumulation and depletion and on runoff patterns throughout the basin during the year (Sections 3.2 and 3.4).

8. The major source of summer streamflow is the inventory of snowpack accumulated during winter. At higher elevations snow often continues to accumulate throughout May at the same time that runoff from melting at lower elevations causes hydrographs to rise (Section 2.3).

9. Permanent snowfields and glaciers predominate in mountain areas above 2400 m and about 10 percent of the drainage area of the Mica project exceeds this elevation. The major sources of runoff are the plateau areas between El. 1800 and 2400; these tend to provide less variability in runoff from year to year than is experienced in the southern parts of the Kootenay basin where the elevations are lower resulting in lesser but more variable runoff. The Canadian portions of the basin tend to provide a less variable and higher runoff per unit area from year to year than the United States portions (Sections 2.1, 2.2).

10. Since maximum snowmelt rates in the basin rarely exceed 80 mm in 1 day, areas of snow cover rather than the depth of snow are more important to the production of peak river discharges from snowmelt. The elevation of the snowline, which governs the snow-covered area, is therefore an important consideration in estimating peak runoff from snowmelt (Section 4.2).

11. Maximum discharges in the Columbia River at the project site usually occur in mid-June and approximately 60 percent of the annual runoff volume occurs in the months of May, June and July. In the Kootenay River drainage area most of the runoff has occurred by the end of June; the sustained high July flows at the project site come from snowmelt in higher elevations of the mainstem Columbia drainage (Section 2.4).

12. At the project site streamflows have been recorded for 67 years and show less variability in annual runoff than precipitation in the upstream drainage areas. Annual runoff has varied from 68 to 125 percent of the long-term average compared to annual precipitation which has ranged between 65 and 140 percent of the average over the same period (Section 2.4).

13. The average annual volume of runoff at the project site has consisted of a 30 percent contribution from the area regulated by the Mica project, 25 percent from the area downstream from Mica and regulated by the Arrow Lakes project, and 40 percent from areas draining to Kootenay Lake and partially regulated by the Duncan and Libby projects. In any given year this pattern of yield may vary from the average (Section 2.4).

14. The greatest flood known occurred in 1894, before streamflow measurements commenced near the project site. The peak unregulated discharge, estimated by the Corps of Engineers from high watermarks further downstream and on the Pend d'Oreille River, was 13 000 m^3/s at the Murphy Creek Project site (Section 3.3).

15. The maximum average daily discharge of record was 10 600 m^3/s at the project site in June of 1961. This discharge was not regulated by the Columbia River Treaty projects.

16. Coincident with the availability of the expanded data base, actual streamflow measurements of record floods occurred in 1972 and 1974 on the tributary area of the Columbia River. These record runoff rates were reduced from a potential peak of 10 600 m^3/s by treaty reservoir operations; the events provided opportunity for calibration and detailed analysis with the UBC Watershed Model for severe runoff conditions (Sections 3.2, 3.3).

17. The most important aspects of the calibration of the UBC Watershed Model of basin-wide runoff production upstream of Trail are the correct representation of the cumulative volumes and the hydrograph shape factors among the various sub-basins (Section 3.8).

18. The calibrated model has been used to reproduce the highest floods of record and provides a sound basis for extrapolating to conditions which could be experienced during a Probable Maximum Flood (Section 3.8, Tables 3-1 through 3-4).

(b) The Probable Maximum Unregulated Flood (PMUF)

1. Snow accumulation prior to a Probable Maximum Flood condition would be similar in areal distribution to the snowpacks recorded in the spring of 1972 and 1974 (Section 3.5).

2. The severe (one in 1000 year) mountain snowpacks were found to be approximately 1.7 times the 1 April average water equivalent in the northern part of the basin and 1.9 times this average in the southern part (Section 4.2).

3. Probable maximum snowmelt runoff will occur as the result of a heavy snowpack over most of the watershed above the Murphy

Creek project site at a time when there is an extended duration of severe temperatures (Section 4.3).

4. Over a 3-day period, the Probable Maximum Rain event would provide a variable depth from over 180 mm at the storm centre over the Arrow Lakes to lesser amounts on adjacent areas of the basin. The total rainfall would amount to more than 80 mm over a 51 800 km^2 area of the watershed. It was assumed in the derivation of the Probable Maximum Flood that the Probable Maximum Rain event could occur at any time in June or July (Section 4.4).

5. Compared to snowmelt, major rainfall inputs have additional significance because they cannot be forecasted (Section 4.4).

(c) The Probable Maximum Regulated Flood (PMRF)

1. Treaty reservoir operations which regulate early summer runoff will, in some years, lead to the annual peak discharge occurring in late summer, instead of early summer, as a result of severe rainfall superimposed in the snowmelt recession (Section 2.4).

2. Once reservoirs have reached normal full pool levels, since additional surcharge above these levels is not permitted, regulated flows at Trail may be higher than the unregulated flows which would have induced a natural surcharge on the upper and lower Arrow Lakes (Section 4.6(e)).

3. During PMF conditions it is reasonable to assume that Arrow reservoir would be operated to achieve local flood control objectives at Trail since these would probably not be in conflict with downstream flood control objectives (Section 4.6(d)).

4. For floods of lesser magnitude than the PMUF and the PMRF, damage could occur at upstream locations while reservoir operations lead to effective flood control at The Dalles (Section 4.6(b)).

5. The Probable Maximum Regulated Flood (PMRF), for use in assessing spillway requirements at the Murphy Creek project site, is 13 100 m^3/s (Section 4.6(e)).

6. The treaty reservoirs provide effective flood control for the Murphy Creek project site and regulate the 19 900 m^3/s Probable Maximum Unregulated Flood (PMUF) to a discharge of 9500 m^3/s. This regulated discharge is lower than the 13 100 m^3/s which could result from a Probable Maximum Runoff in early August immediately following refill of the Treaty reservoirs (Section 4.6(e)).

SECTION 6.0 - CONCLUSIONS

1. The Probable Maximum Regulated Flood (PMRF) was calculated to be 13 100 m^3/s and to occur in early August immediately following the refill of the Treaty reservoirs (Section 4.6(e)).

2. The Probable Maximum Unregulated Flood (PMUF) was calculated to be 19 900 m^3/s and to occur in early June. Considerable storage would be available in the Columbia River Treaty reservoirs at this time, and it was shown that the Treaty reservoirs would provide effective flood control for the Murphy Creek project site and regulate the 19 900 m^3/s PMUF to a maximum discharge of 9500 m^3/s. This regulated discharge is lower than the early August event of 13 100 m^3/s referred to above as the Probable Maximum Regulated Flood (Section 4.6(d)).

SECTION 7.0 - RECOMMENDATIONS

It is recommended that:

1. A peak discharge of 13 100 m³/s be adopted as the Probable Maximum Flood at the Murphy Creek project site. This discharge results from an early August flood event immediately following the refill of the Columbia River Treaty reservoirs.

2. The possibility of postponing the 31 July filling date of the Mica project reservoir by 2 to 4 weeks under conditions leading to the Probable Maximum Flood at the Murphy Creek project site should be checked prior to final design. Such an extension of the refill period for extremely large floods would be beneficial in reducing the Probable Maximum Flood for the Murphy Creek project.

REFERENCES

1. "Criteria and Practices Utilized in Determining the Required Capacity of Spillway". 1970. U.S. Committee: Int. Commission on Large Dams. USCOLD Committee on Failures and Accidents to Large Dams other than in Connection with Foundations.

2. "Lower Columbia River Standard Project Flood and Probable Maximum Flood". Memorandum Report: Columbia River Basin. September, 1969. U.S. Army, Engineer Division, N. Pacific, Portland, Oregon.

3. "A Study of Probable Maximum Rainfall for Three Watersheds in Southeastern British Columbia". D. Storr, Storr Water Resources Consulting Service, Ganges, B.C., and K.F. Harry, Duncan, B.C.: A Report Submitted to B.C. Hydro and Power Authority for the Murphy Creek Project Probable Maximum Flood Study. January 1981.

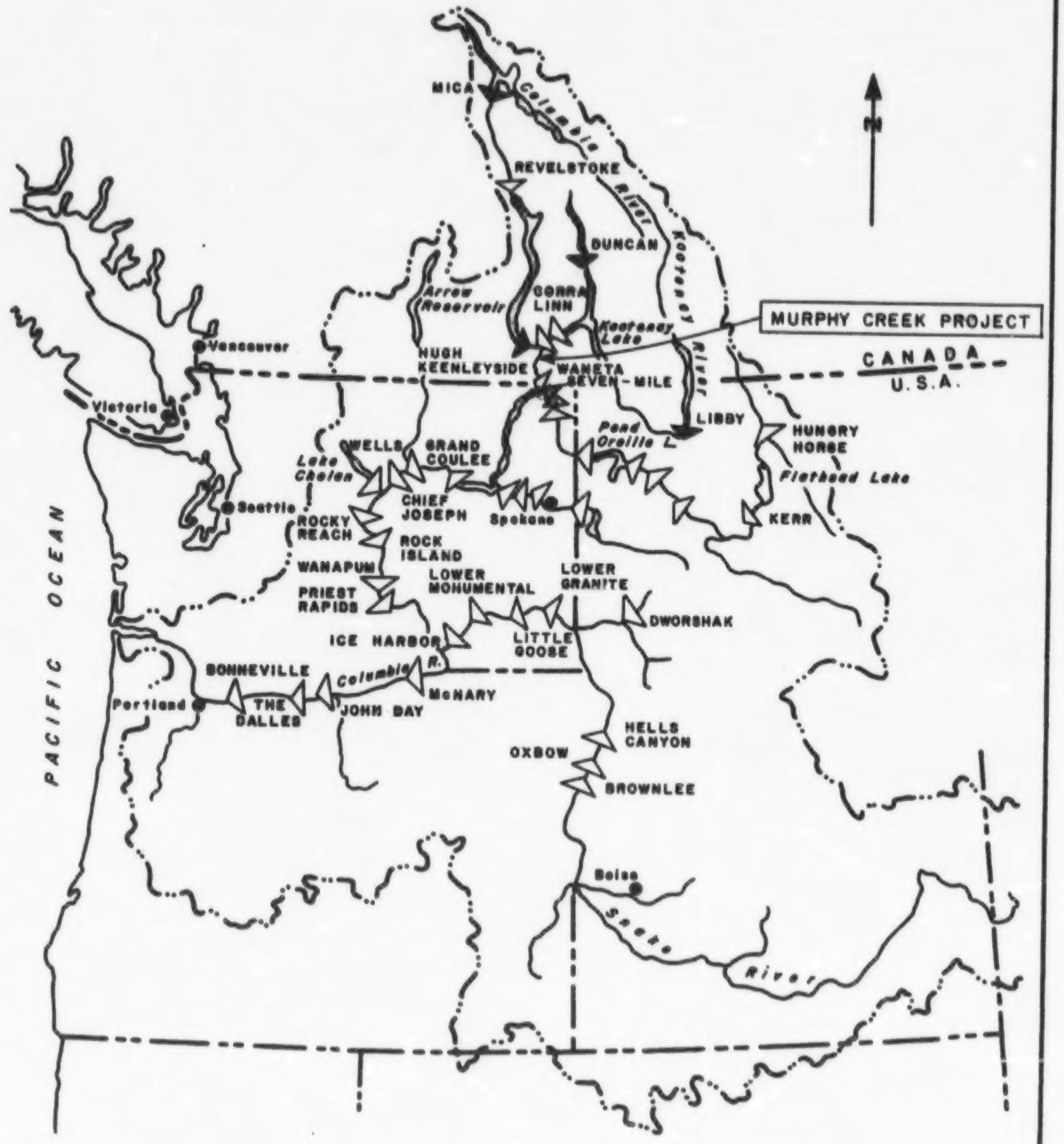
4. "U.B.C. Watershed Model", M.C. Quick and A. Pipes. Hydrological Sciences Bulletin, XXII, 1 3 (1977).

5. "A Combined Snowmelt and Rainfall Runoff Model". Canadian Journal of Civil Engineering 3, No. 3. pp. 449-460 (1976).

6. "Non-linear Channel Routing by Computer". Journal of Hydraulic Divn., Proc. Amer. Soc. Civ. Engrs. February (1975).

7. "Columbia River Treaty Principles and Procedures for the Preparation and Use of Hydroelectric Operating Plans". Columbia River Treaty Operating Committee. May 1979.

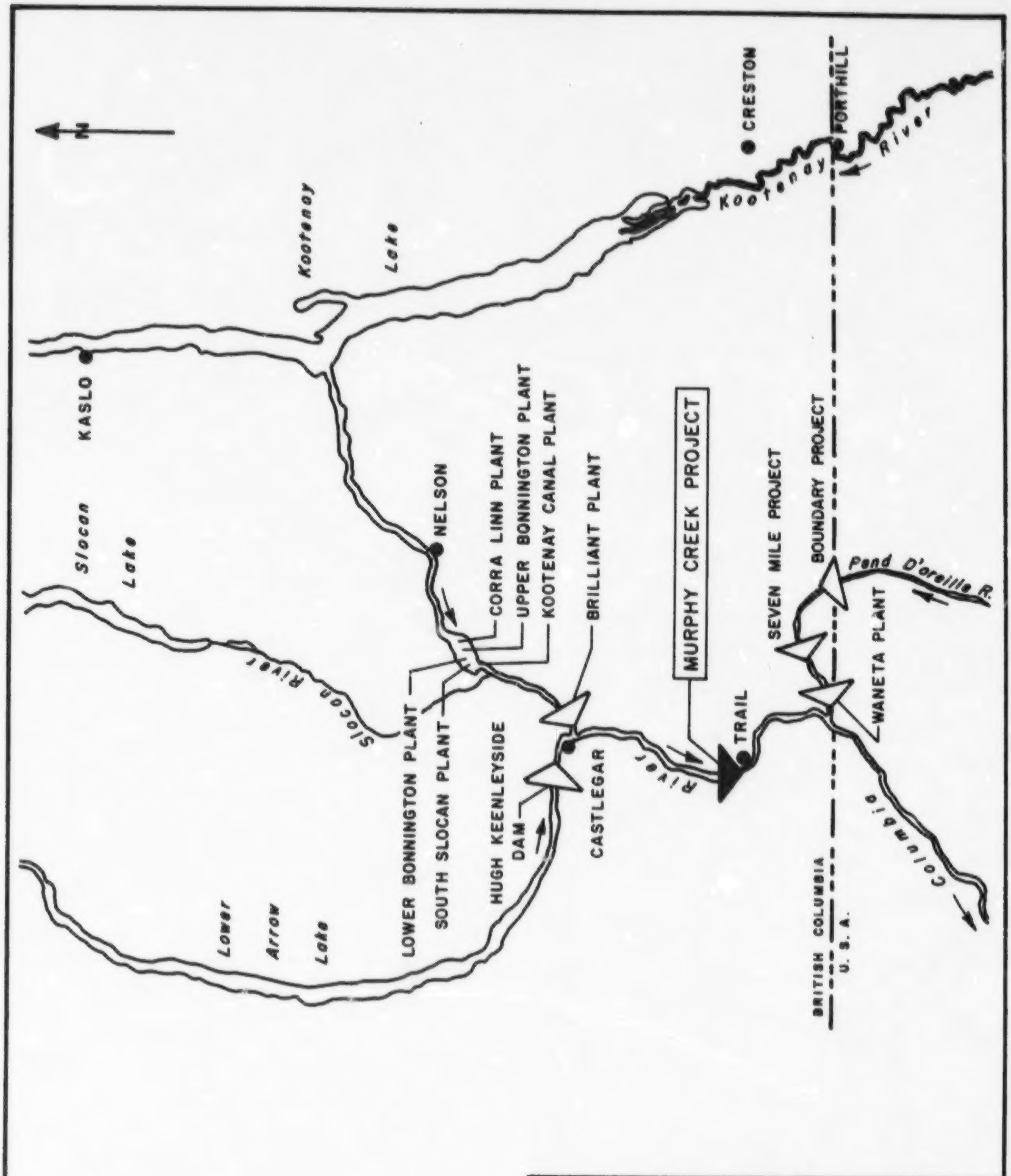
8. "Columbia River Treaty-Flood Control Operating Plan". U.S. Corps of Engineers, N. Pacific Division. October 1972.


MICA
Columbia River
REVELSTOKE
DUNCAN
Kootenay River
Arrow Reservoir
CORRA LINN
Kootenay Lake
MURPHY CREEK PROJECT
HUGH KEENLEYSIDE
WANETA
SEVEN - MILE
CANADA
U.S.A.
Vancouver
Victoria
LIBBY
HUNGRY HORSE
Pend Oreille L.
WELLS
GRAND COULEE
Lake Chelan
Flathead Lake
CHIEF JOSEPH
Seattle
Spokane
KERR
ROCKY REACH
ROCK ISLAND
PACIFIC OCEAN
WANAPUM
LOWER MONUMENTAL
LOWER GRANITE
PRIEST RAPIDS
DWORSHAK
ICE HARBOR
LITTLE GOOSE
BONNEVILLE
Columbia R.
McNARY
Portland
THE DALLES
JOHN DAY
HELLS CANYON
OXBOW
BROWNLEE
Boise
Snake River
Scale: 100 0 100 200 km
LEGEND
Treaty projects
Other projects

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

MAP OF THE COLUMBIA RIVER BASIN

DATE MAY 1980	FIG. 2-1
DWN D.J.	DWG No.


N
KASLO
Kootenay
Lake
CRESTON
PORTHILL
Kootenay
River
Slocan
Lake
Slocan River
NELSON
CORRA LINN PLANT
UPPER BONNINGTON PLANT
KOOTENAY CANAL PLANT
LOWER BONNINGTON PLANT
SOUTH SLOCAN PLANT
BRILLIANT PLANT
MURPHY CREEK PROJECT
SEVEN MILE PROJECT
BOUNDARY PROJECT
Pend D'oreille R.
WANETA PLANT
TRAIL
River
HUGH KEENLEYSIDE DAM
CASTLEGAR
Lower
Arrow
Lake
Columbia
BRITISH COLUMBIA
U. S. A.

LEGEND

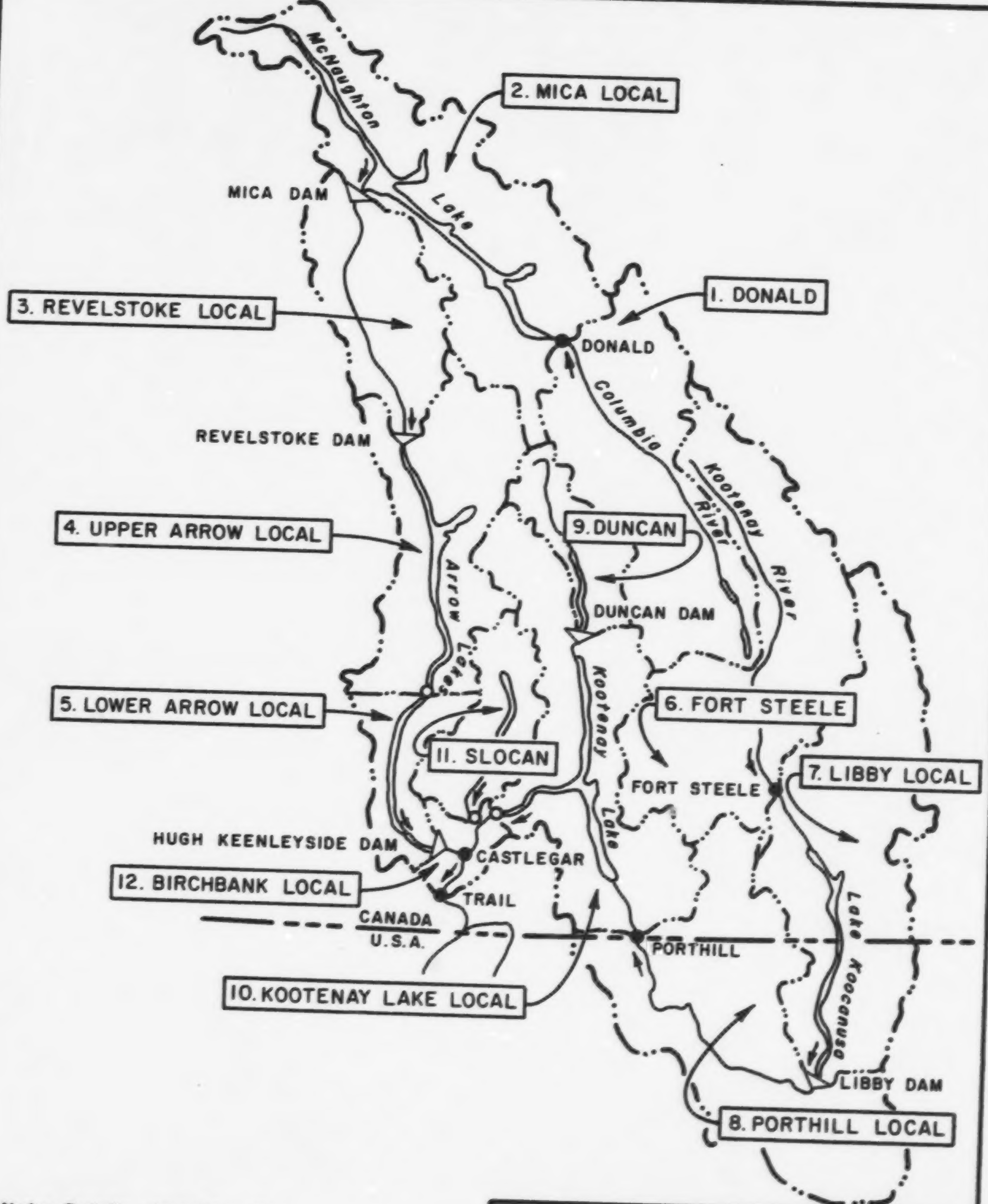
△ *Existing Projects*

▲ *Proposed Project*

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

LOCATION OF THE MURPHY CREEK PROJECT

DATE MAY 1980	FIG 2-2
DWN D. J.	DWG No.

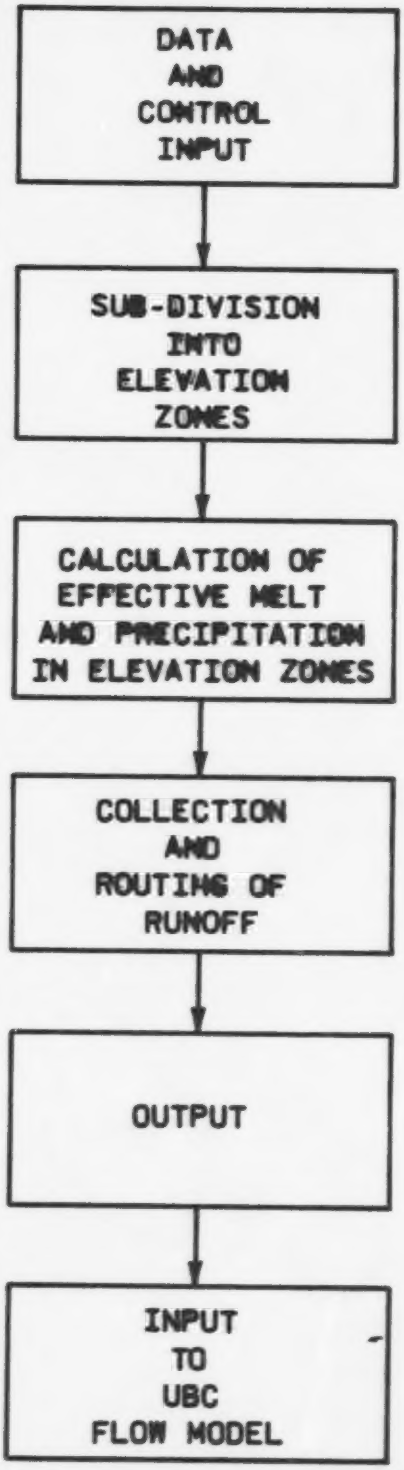

McNaughton
2. MICA LOCAL
MICA DAM
Lake
1. DONALD
3. REVELSTOKE LOCAL
DONALD
Columbia
REVELSTOKE DAM
Kootenay
River
4. UPPER ARROW LOCAL
9. DUNCAN
River
Arrow
DUNCAN DAM
Lakes
Kootenay
5. LOWER ARROW LOCAL
6. FORT STEELE
11. SLOCAN
FORT STEELE
7. LIBBY LOCAL
HUGH KEENLEYSIDE DAM
Lake
CASTLEGAR
12. BIRCHBANK LOCAL
TRAIL
CANADA
U.S.A.
PORTHILL
Lake Koocanusa
10. KOOTENAY LAKE LOCAL
LIBBY DAM
8. PORTHILL LOCAL

Note: Details describing the
drainage subdivisions
are given in Appendix B

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

SUBDIVISION OF THE COLUMBIA RIVER DRAINAGE AREA ABOVE MURPHY CREEK PROJECT

DATE MAY 1980	FIG 3-1
DWN D.J.	DWG No.


DATA AND CONTROL INPUT
SUB-DIVISION INTO ELEVATION ZONES
CALCULATION OF EFFECTIVE MELT AND PRECIPITATION IN ELEVATION ZONES
COLLECTION AND ROUTING OF RUNOFF
OUTPUT
INPUT TO UBC FLOW MODEL

- PHYSICAL AND HYDROLOGICAL DESCRIPTION OF WATERSHED BY AREA AND ELEVATION
- METEOROLOGICAL INPUT DATA
- STREAMFLOWS FOR COMPARISON, IF AVAILABLE
- SPECIFICATION OF PERIOD OF ANALYSIS

- THE HYDROLOGICAL BEHAVIOUR IS ASSESSED BY ELEVATION ZONES
- TEMPERATURE AND PRECIPITATION DATA ARE ADJUSTED FOR ELEVATION

- SOIL MOISTURE AND GROUNDWATER CONTROL ALLOCATES SNOWMELT AND RAIN TO FAST, MEDIUM AND SLOW COMPONENTS OR RUNOFF

- BASIN RUNOFF IS ASSEMBLED INTO A FINAL STREAMFLOW HYDROGRAPH

- CALCULATED AND RECORDED STREAMFLOWS ARE COMPARED DURING CALIBRATION PROCESS

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

SIMPLIFIED SCHEMATIC OF UBC WATERSHED MODEL

DATE MAY 1980

FIG 3 - 2

DWN

DWG. No.

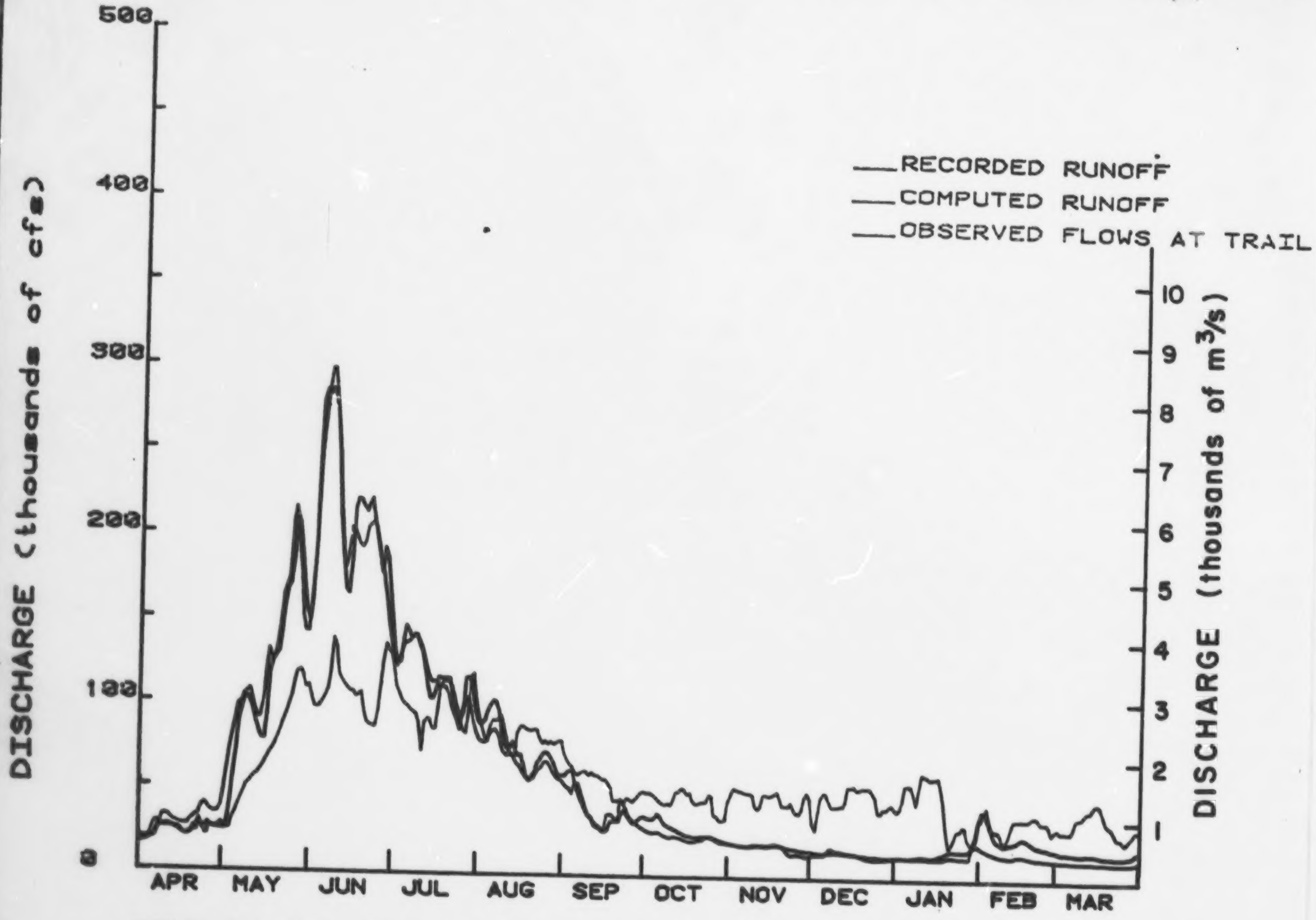


FIGURE 3-3. CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1978

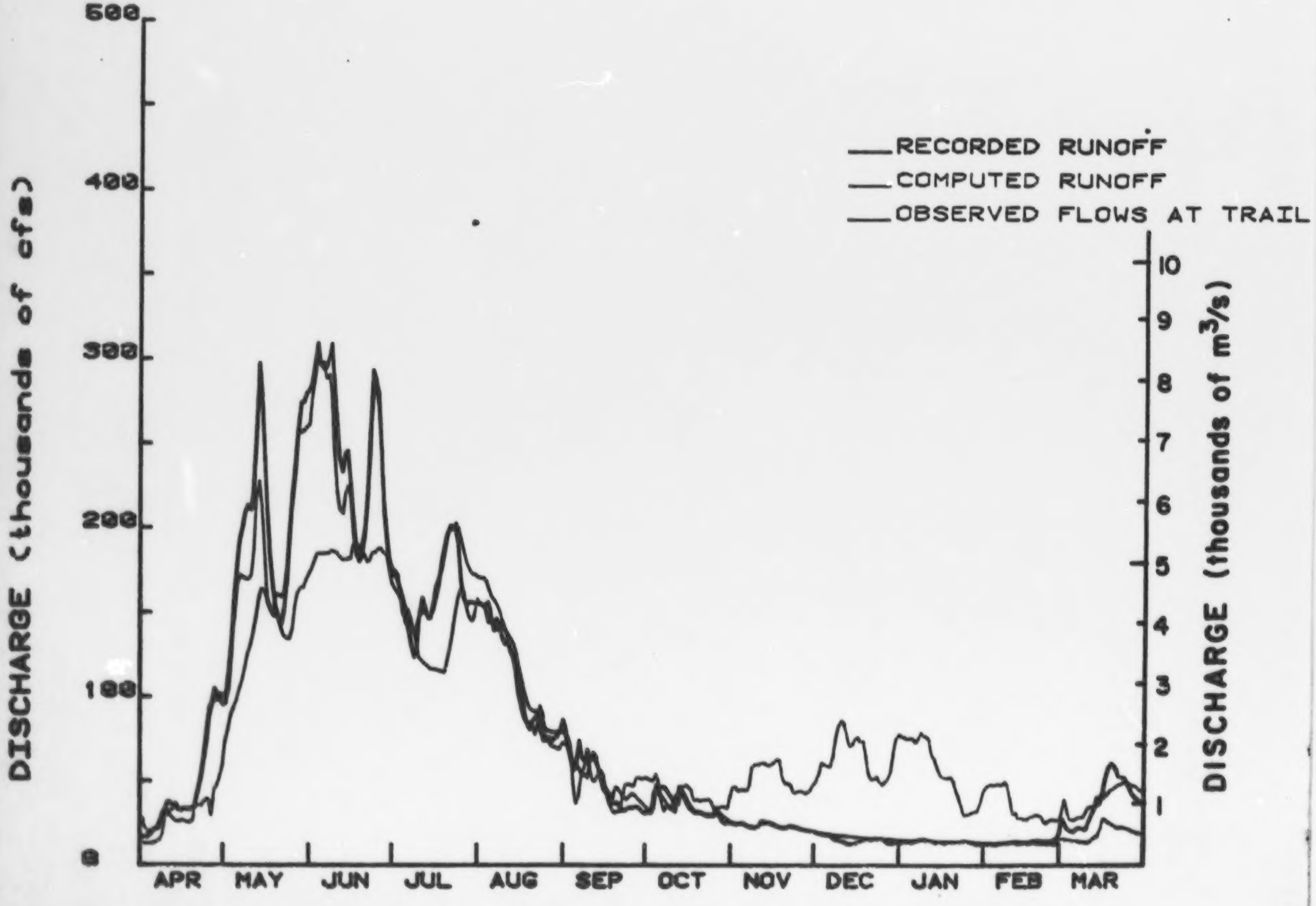


FIGURE 3-4. CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1971

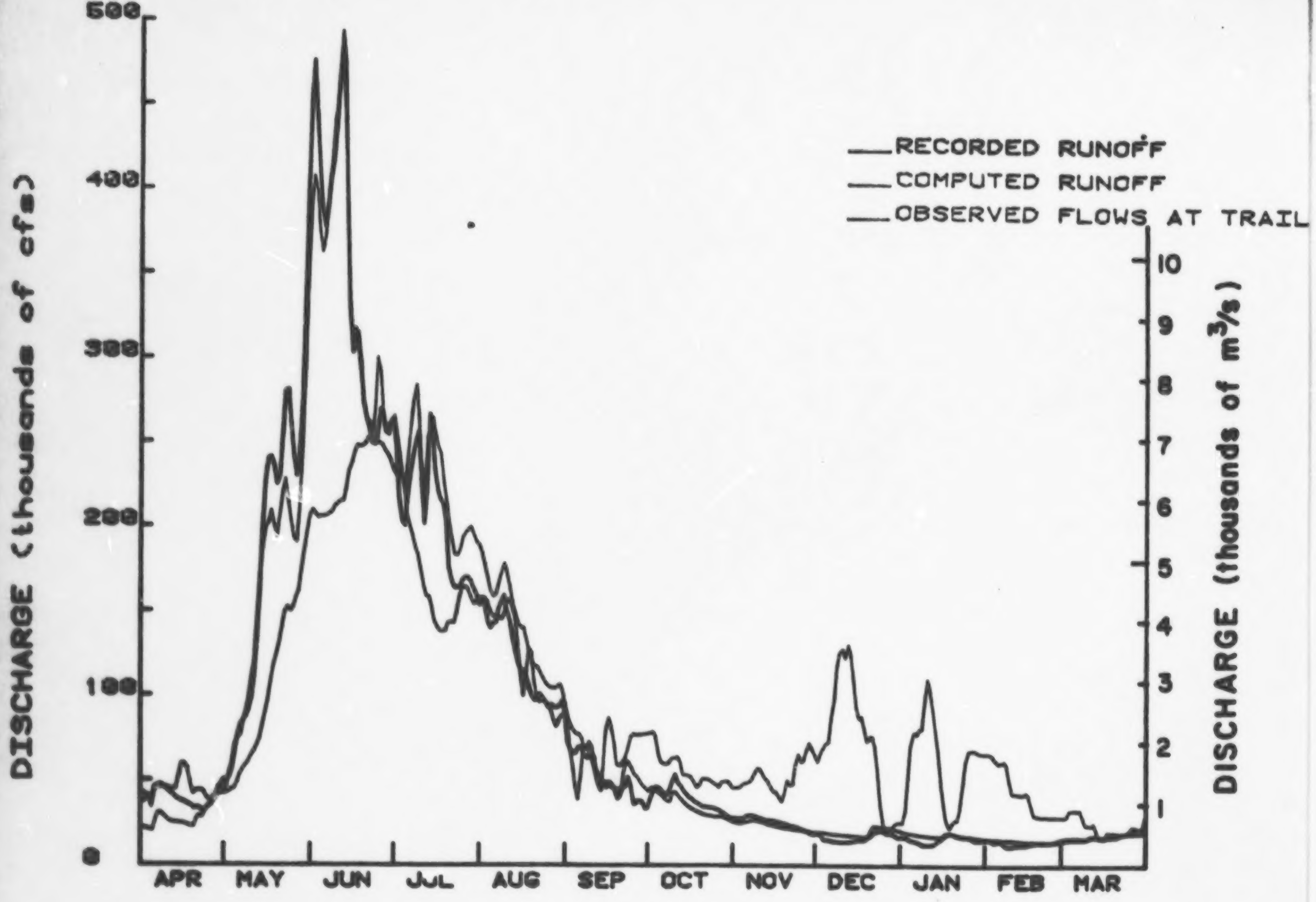


FIGURE 3-5. CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1972

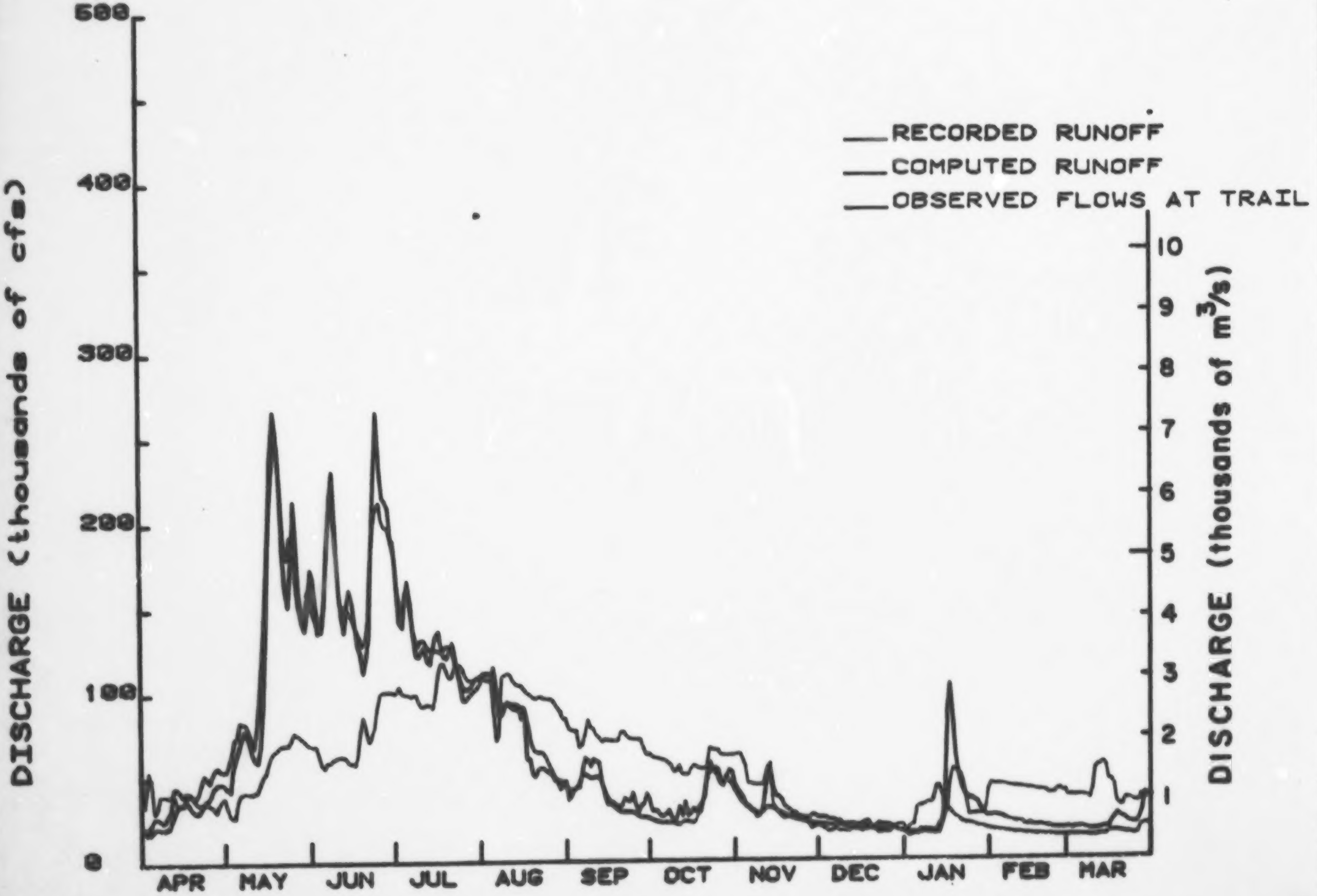


FIGURE 3-6 • CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1973

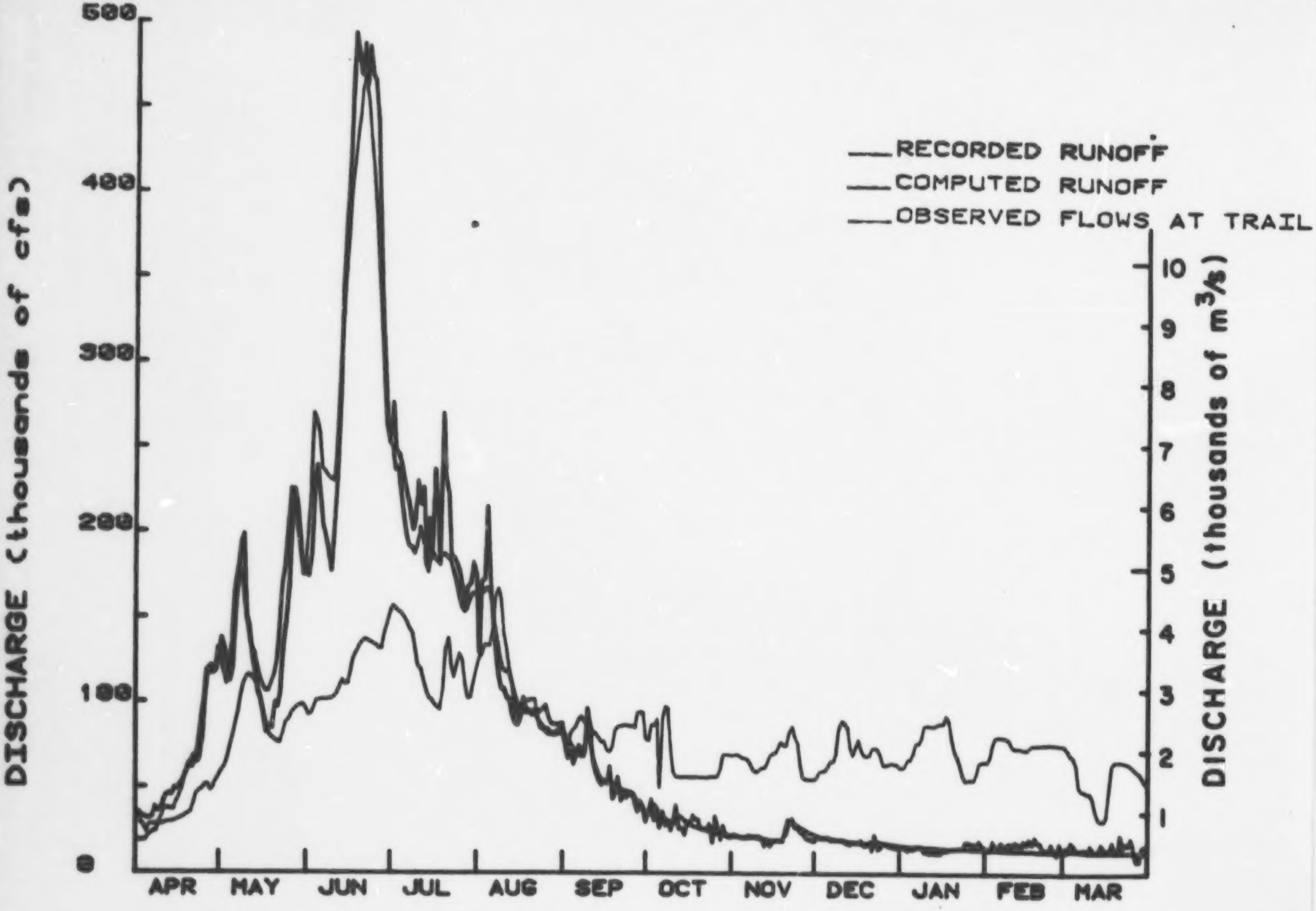


FIGURE 9-7 · CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1974

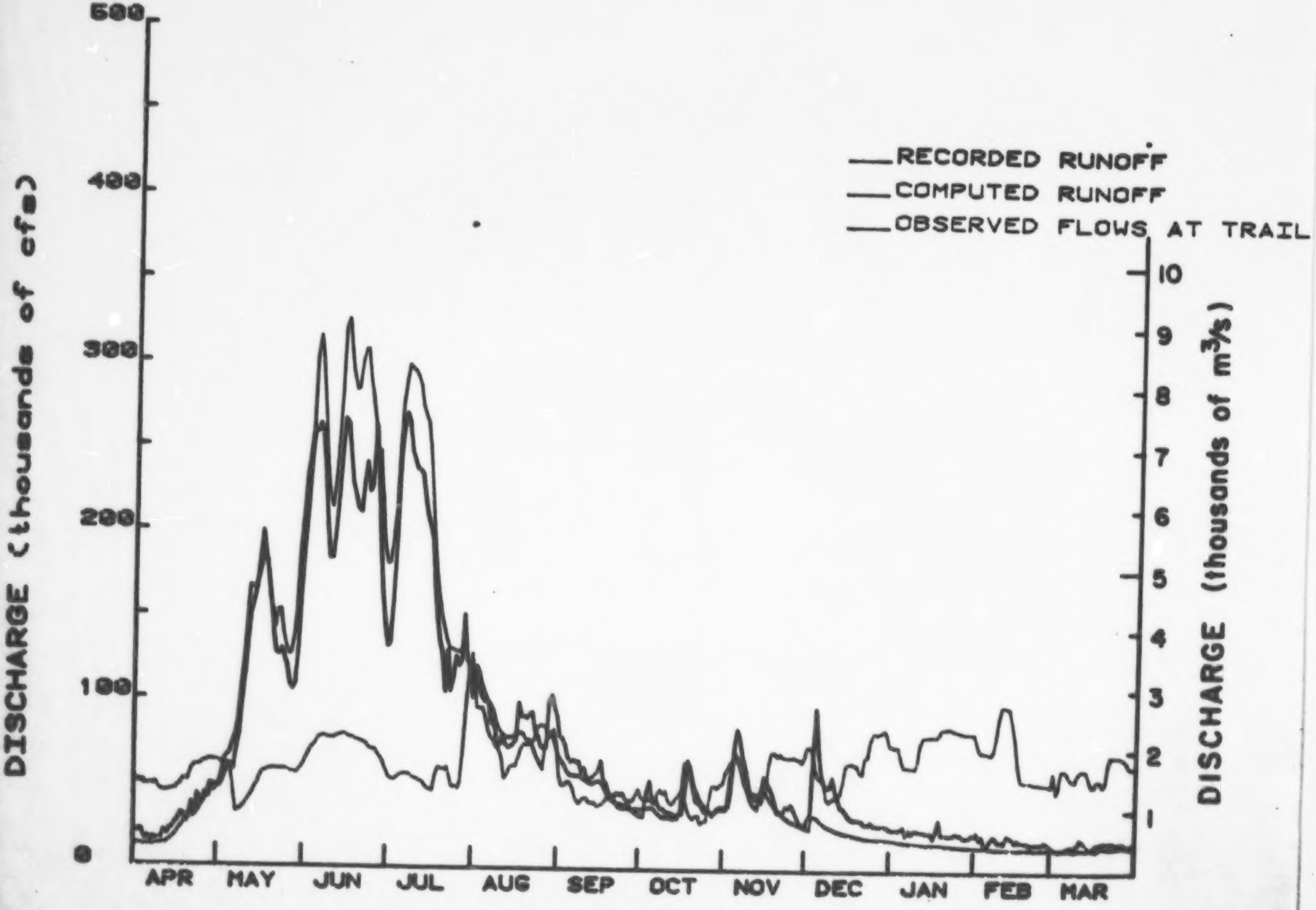


FIGURE 3-6. CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1976

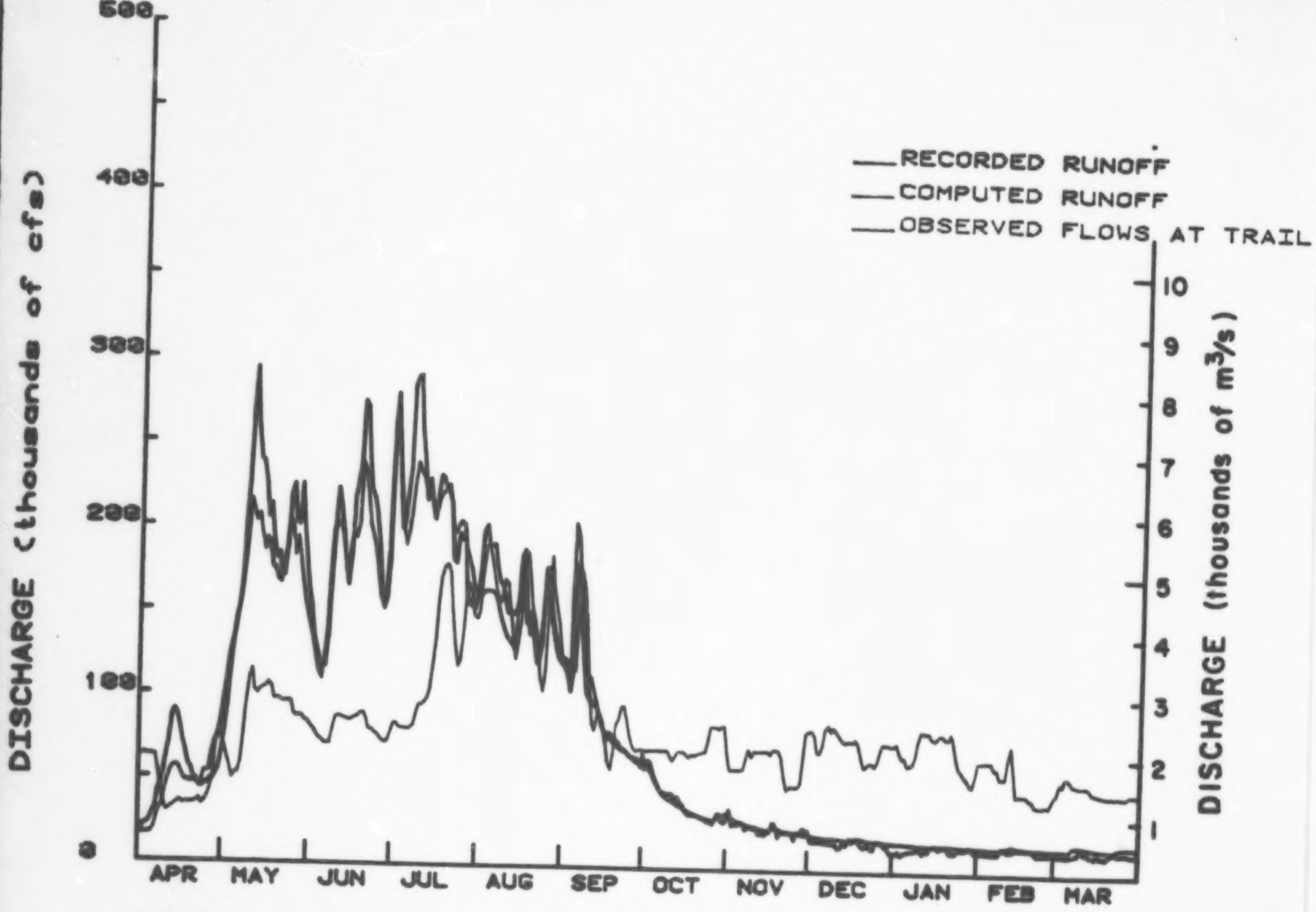


FIGURE 3-8 CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1976

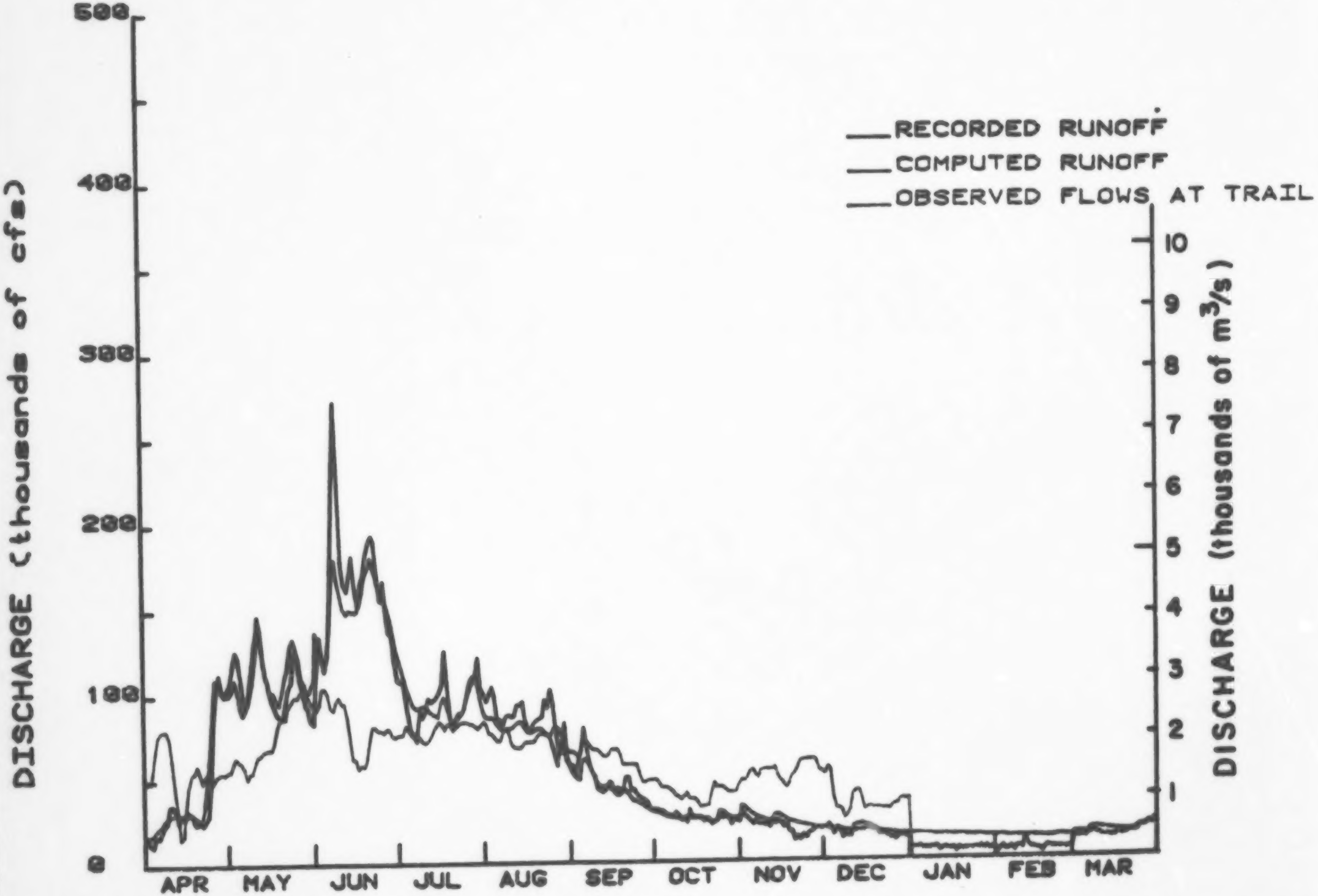


FIGURE 3-18 CALIBRATION OF BASINWIDE RUNOFF PRODUCTION ABOVE MURPHY CREEK-1977

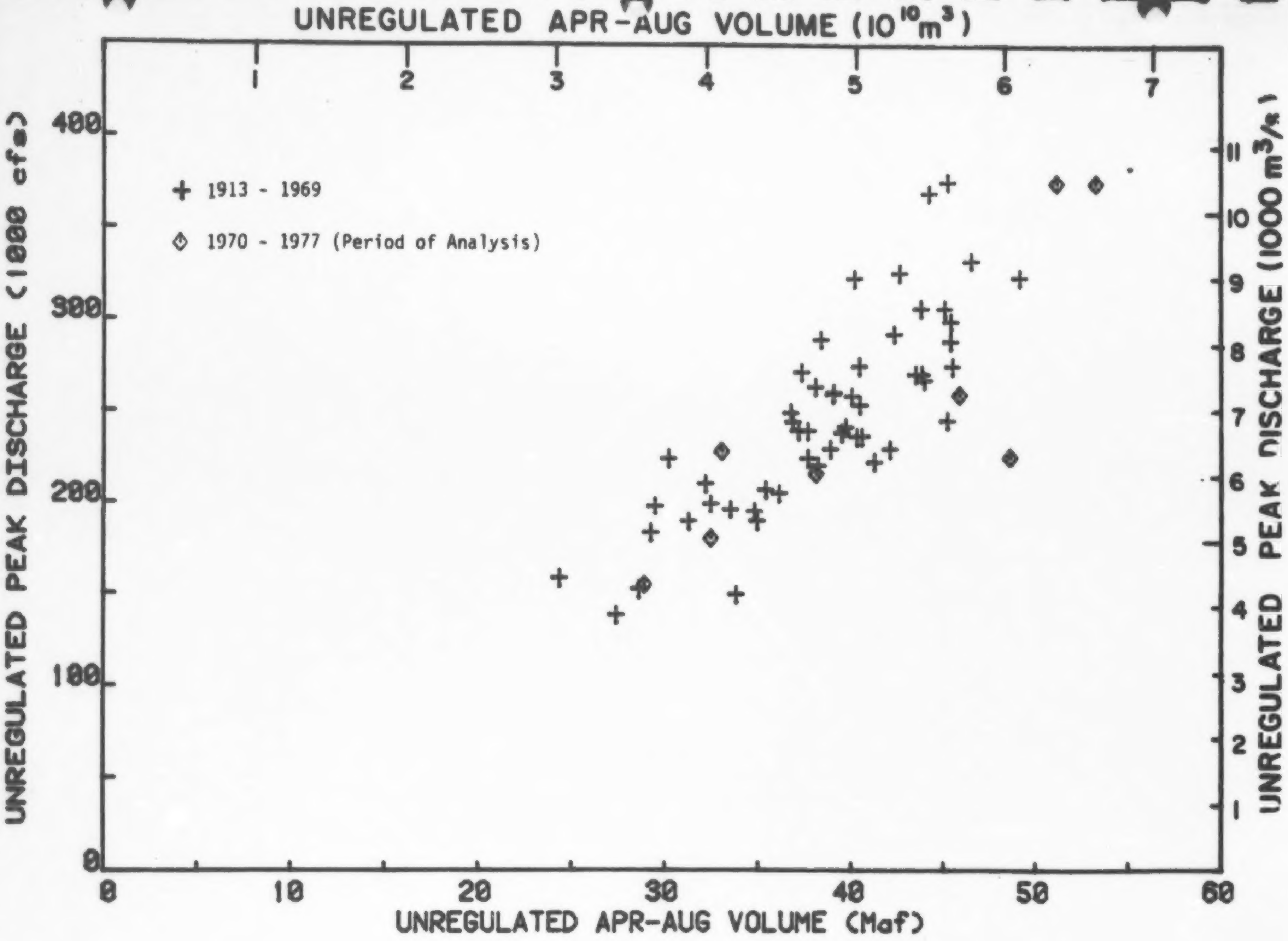


FIGURE 3-11: COLUMBIA R. FLOODS AT TRAIL (PEAK vs. VOLUME)

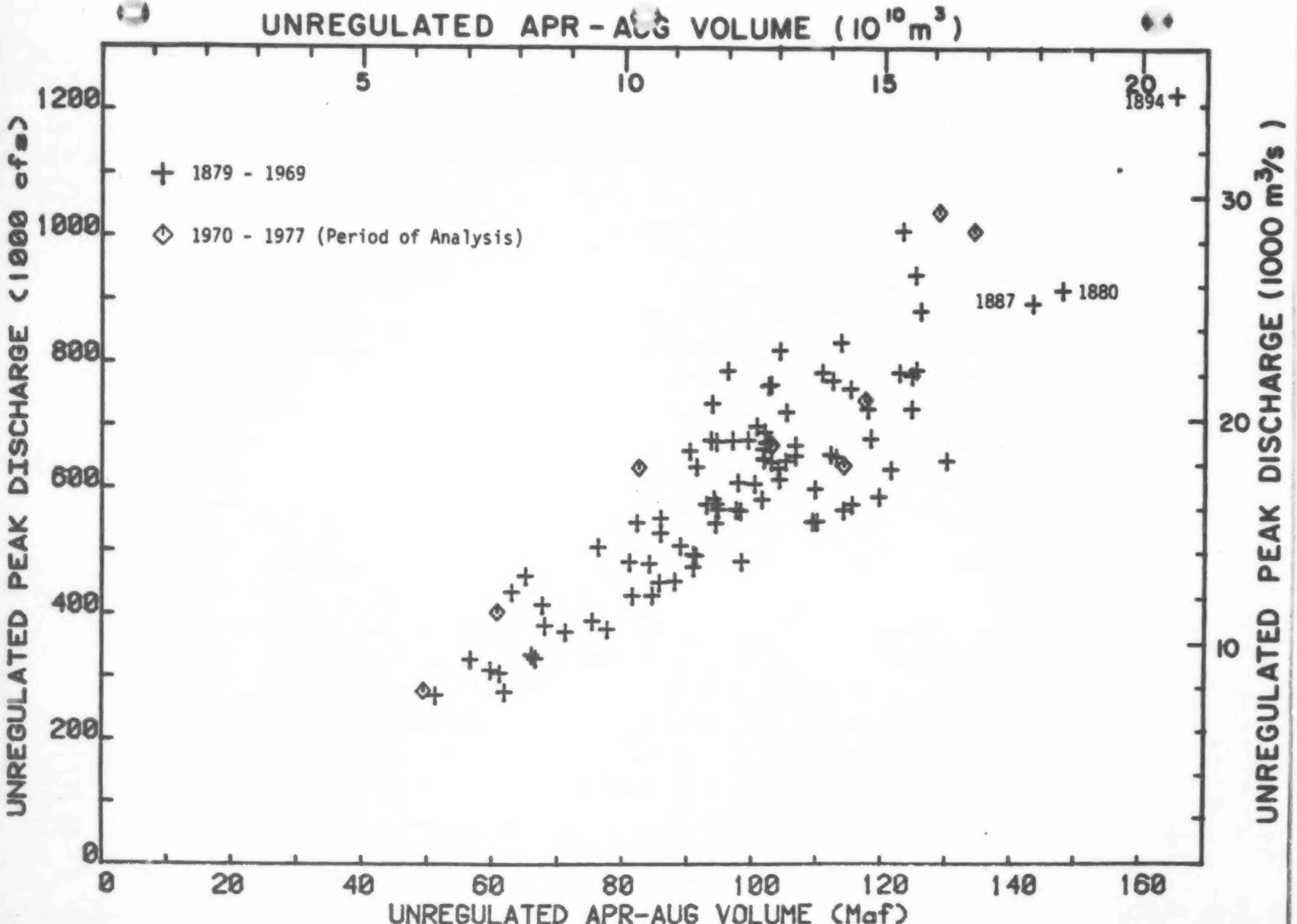
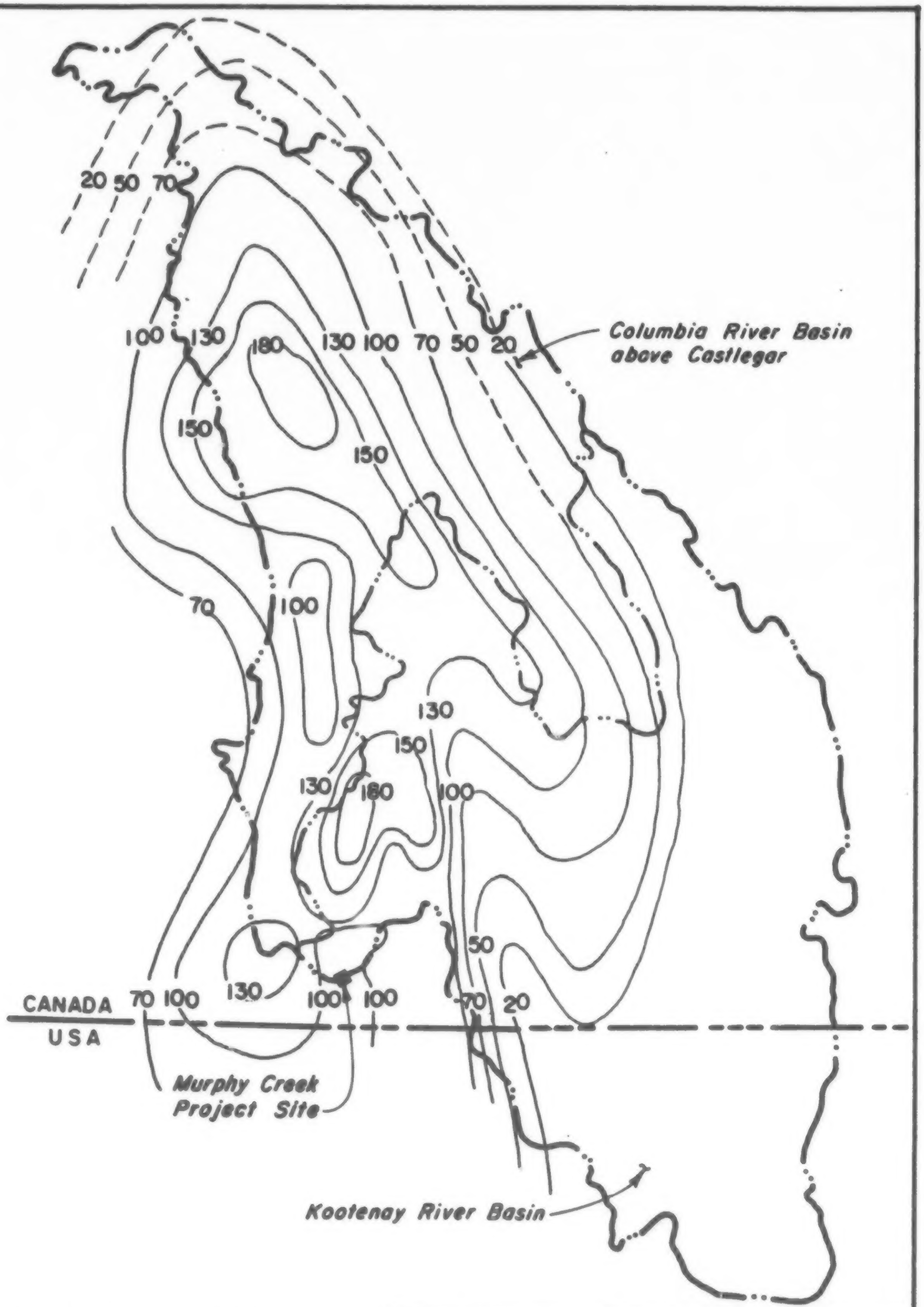


FIGURE 3-12: COLUMBIA R. FLOODS AT THE DALLES (PEAK vs. VOLUME)


20 50 70
100 130 180 130 100 70 50 20
Columbia River Basin above Castlegar
150
150
70
100
130
150
130
180
100
50
CANADA
USA
70 100 130 100 100 70 20
Murphy Creek Project Site
Kootenay River Basin

THREE-DAY PRECIPITATION TOTALS
FOR PMR EVENT SHOWN IN mm

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

ESTIMATED ISOHYETAL PATTERN FOR PROBABLE MAXIMUM RAIN EVENT

DATE MAY 1980

FIG 4 - 1

DWN

DWG. No.

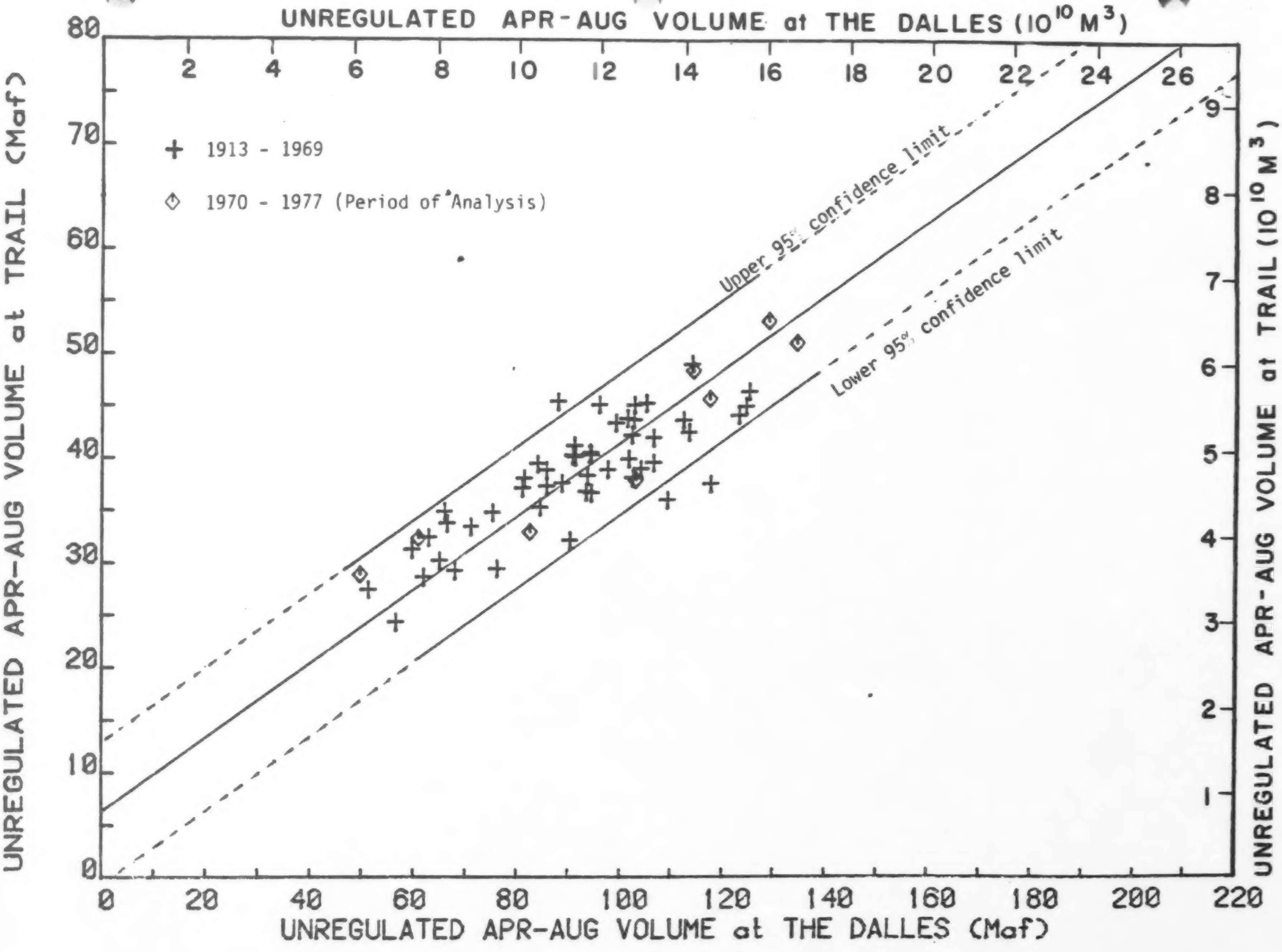


FIGURE 4-2: COLUMBIA R. FLOOD VOLUMES AT THE DALLES AND AT TRAIL

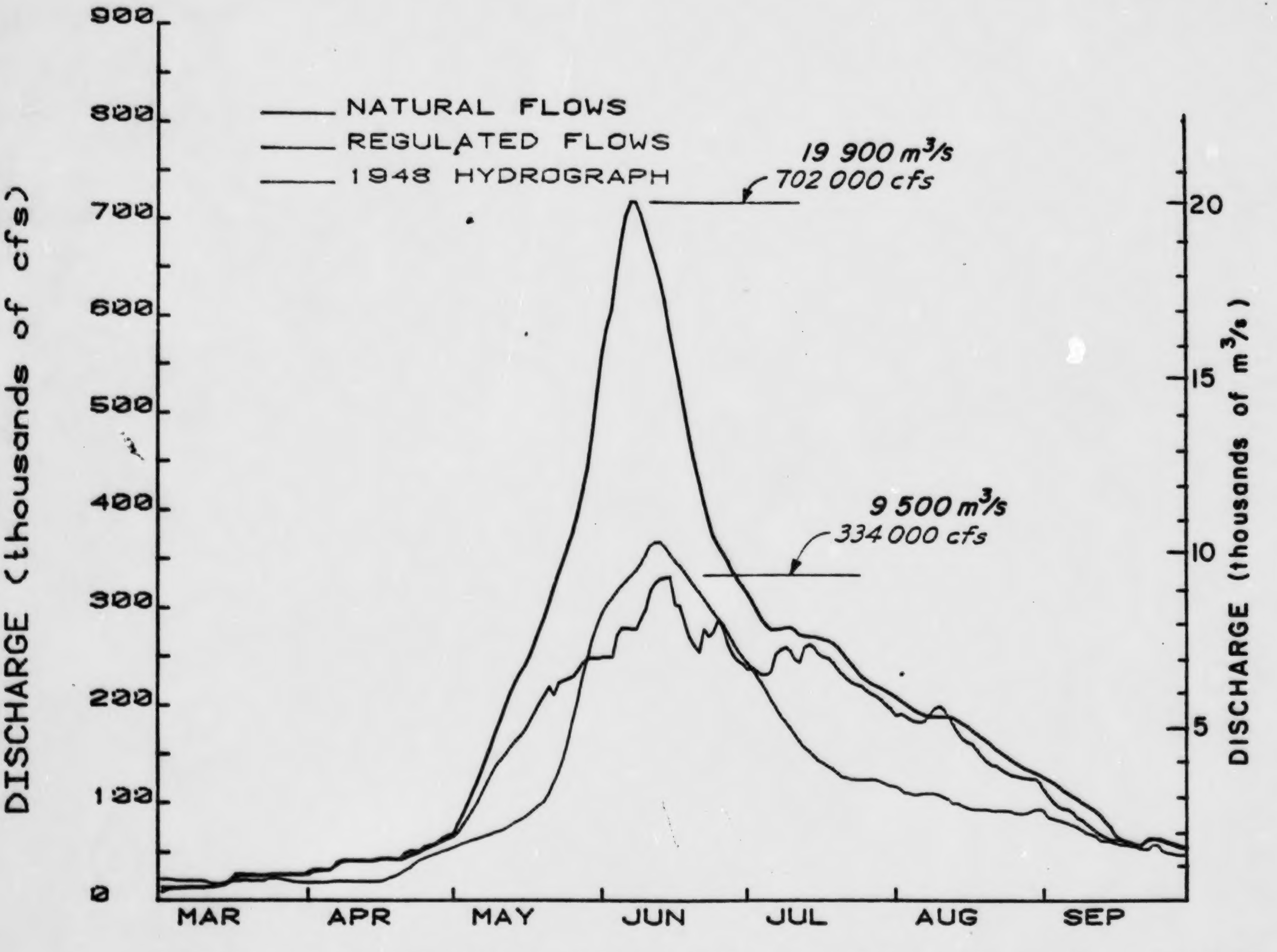


FIGURE 4-3 HYDROGRAPHS AT MURPHY CREEK PROJECT FOR THE PMUF SEQUENCE

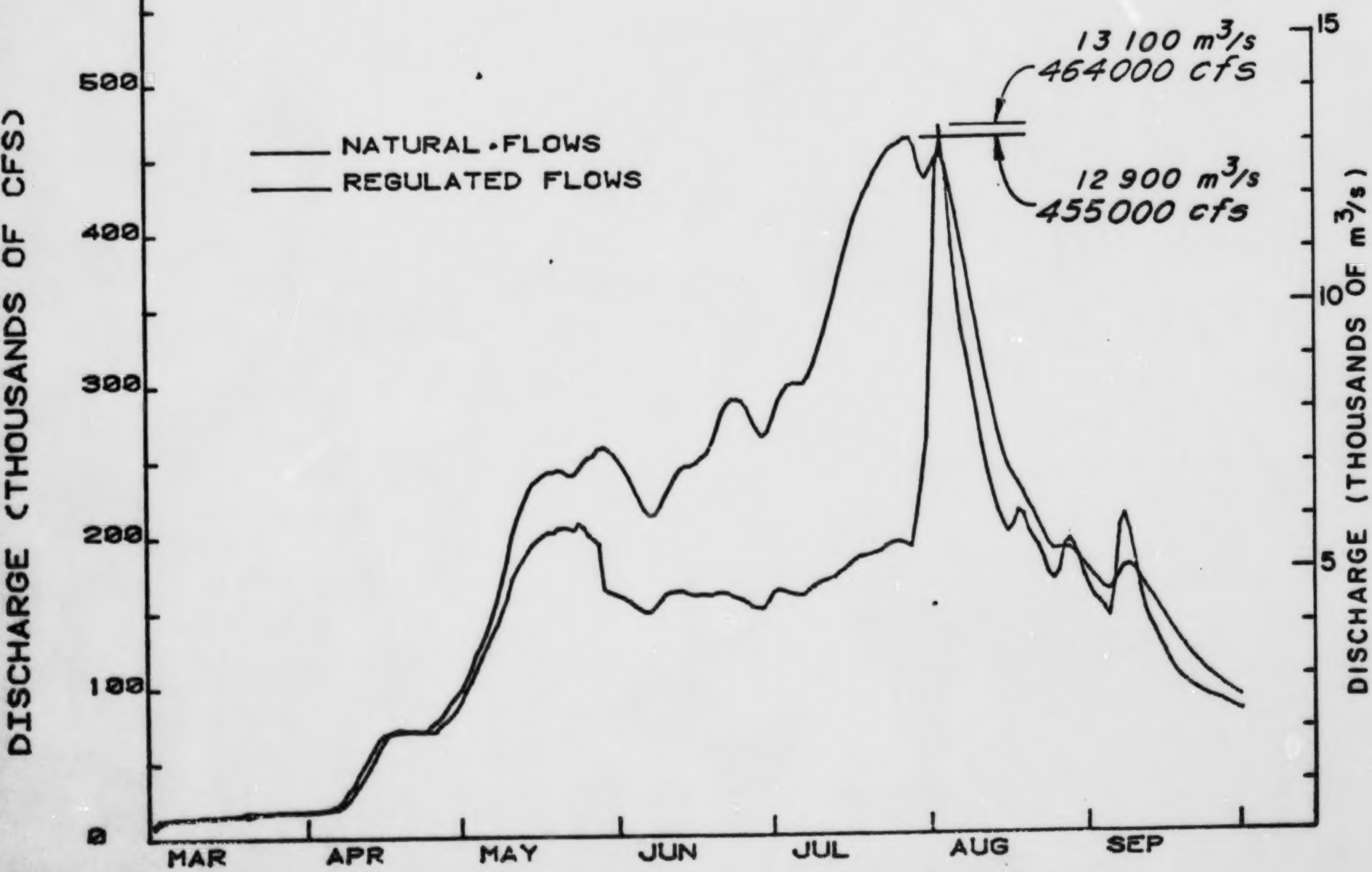


FIGURE 4-4 HYDROGRAPHS AT MURPHY CREEK PROJECT FOR THE PMRF SEQUENCE

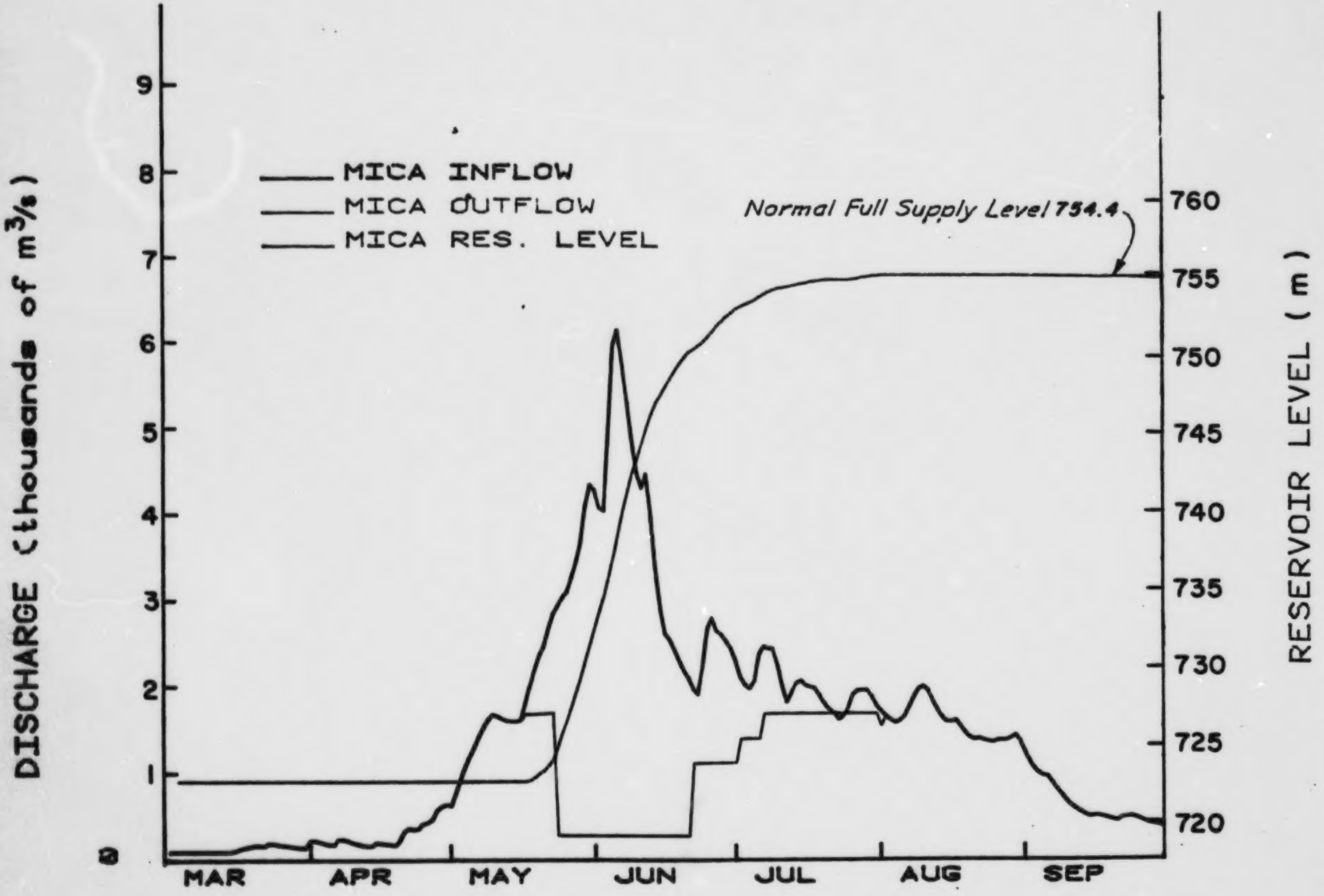


FIGURE 4-5 CONDITIONS AT MICA PROJECT - 72MY81MY31 (PMUF) SEQUENCE

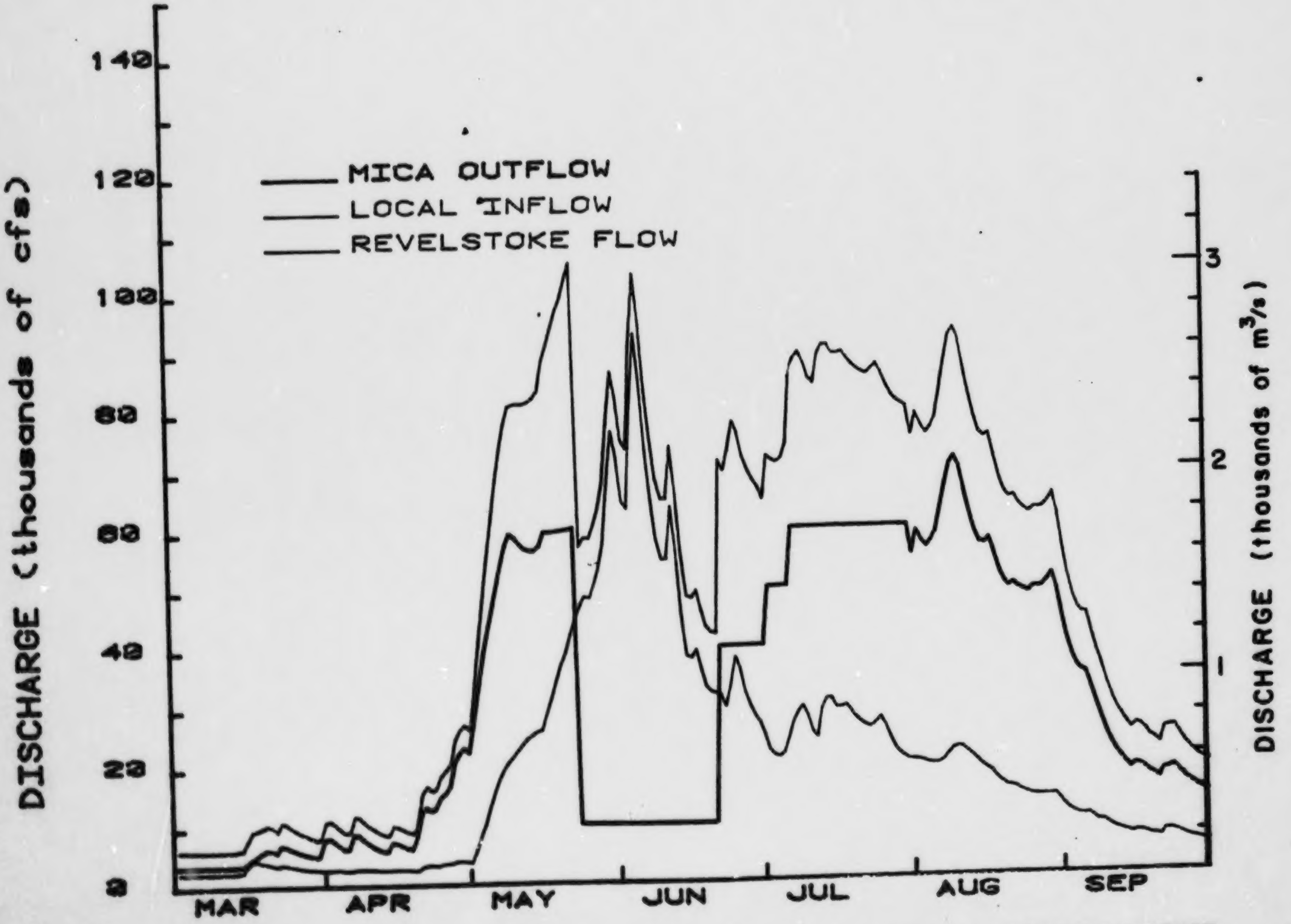


FIGURE 4-6 CONDITIONS AT REVELSTOKE - 72MY01MY31 (PMUF) SEQUENCE

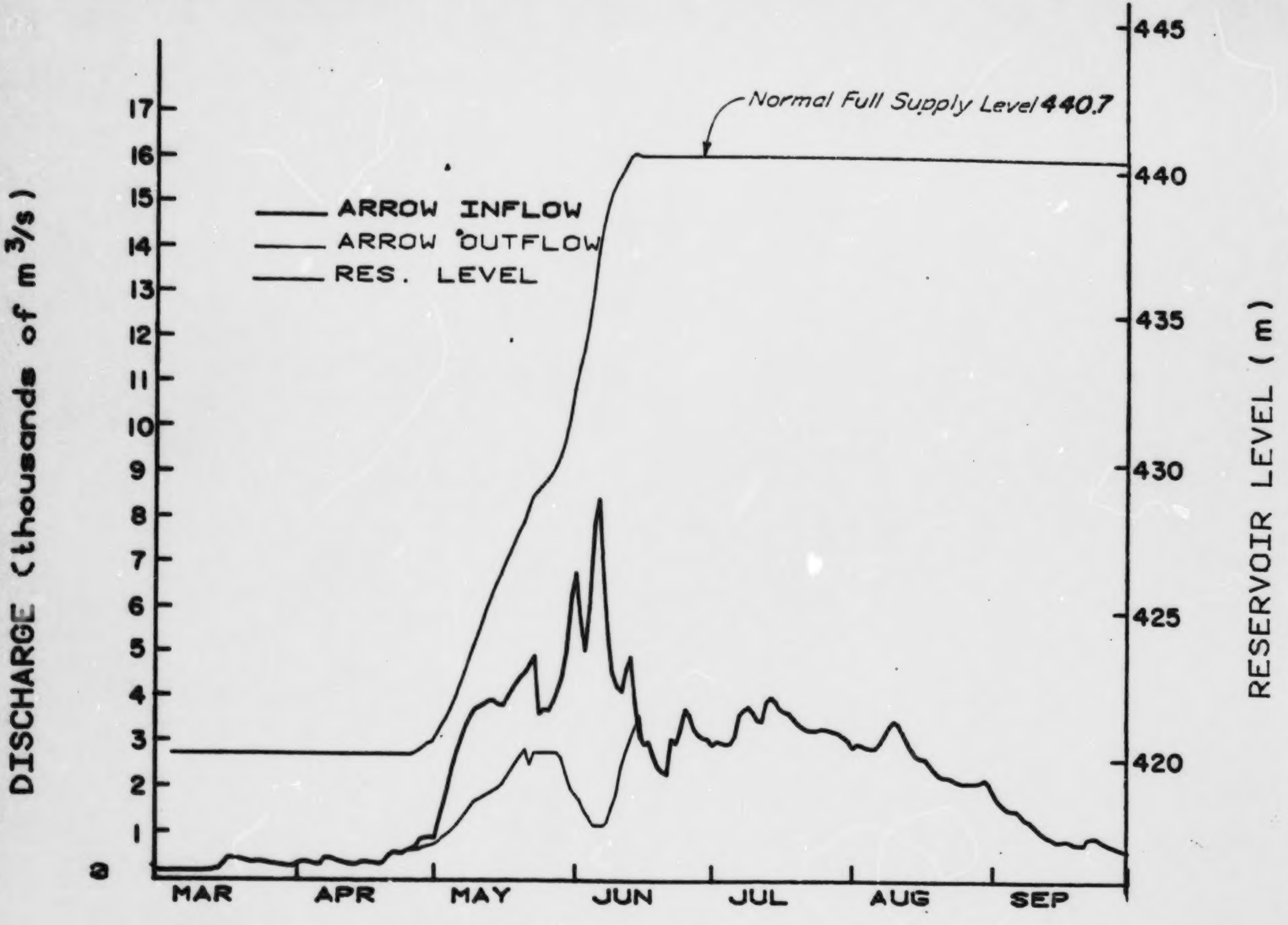


FIGURE 4-7 CONDITIONS AT ARROW PROJECT - 72MY01MY31 (PMUF) SEQUENCE

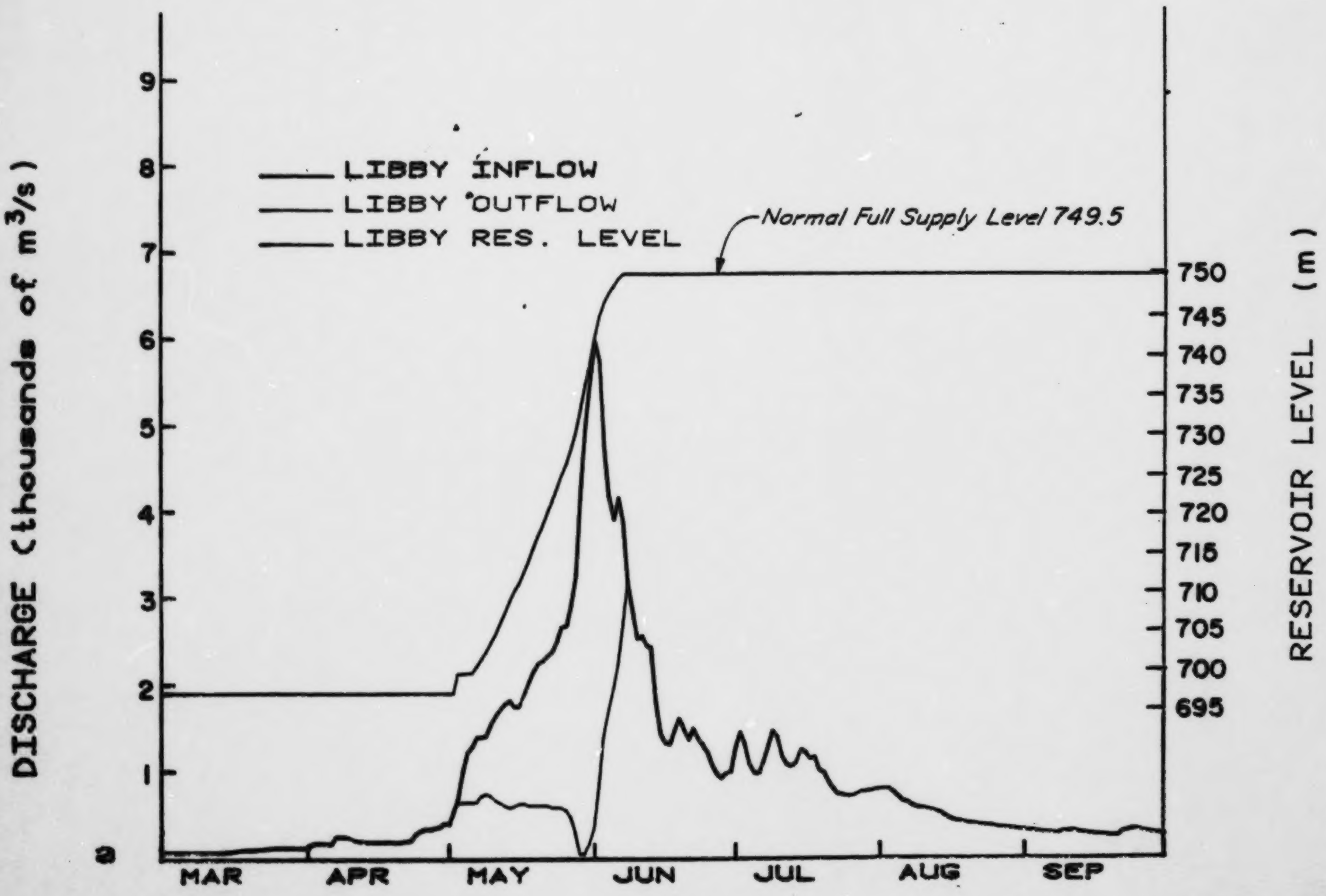


FIGURE 4-8 CONDITIONS AT LIBBY PROJECT - 72MY01MY31 (PMUF) SEQUENCE

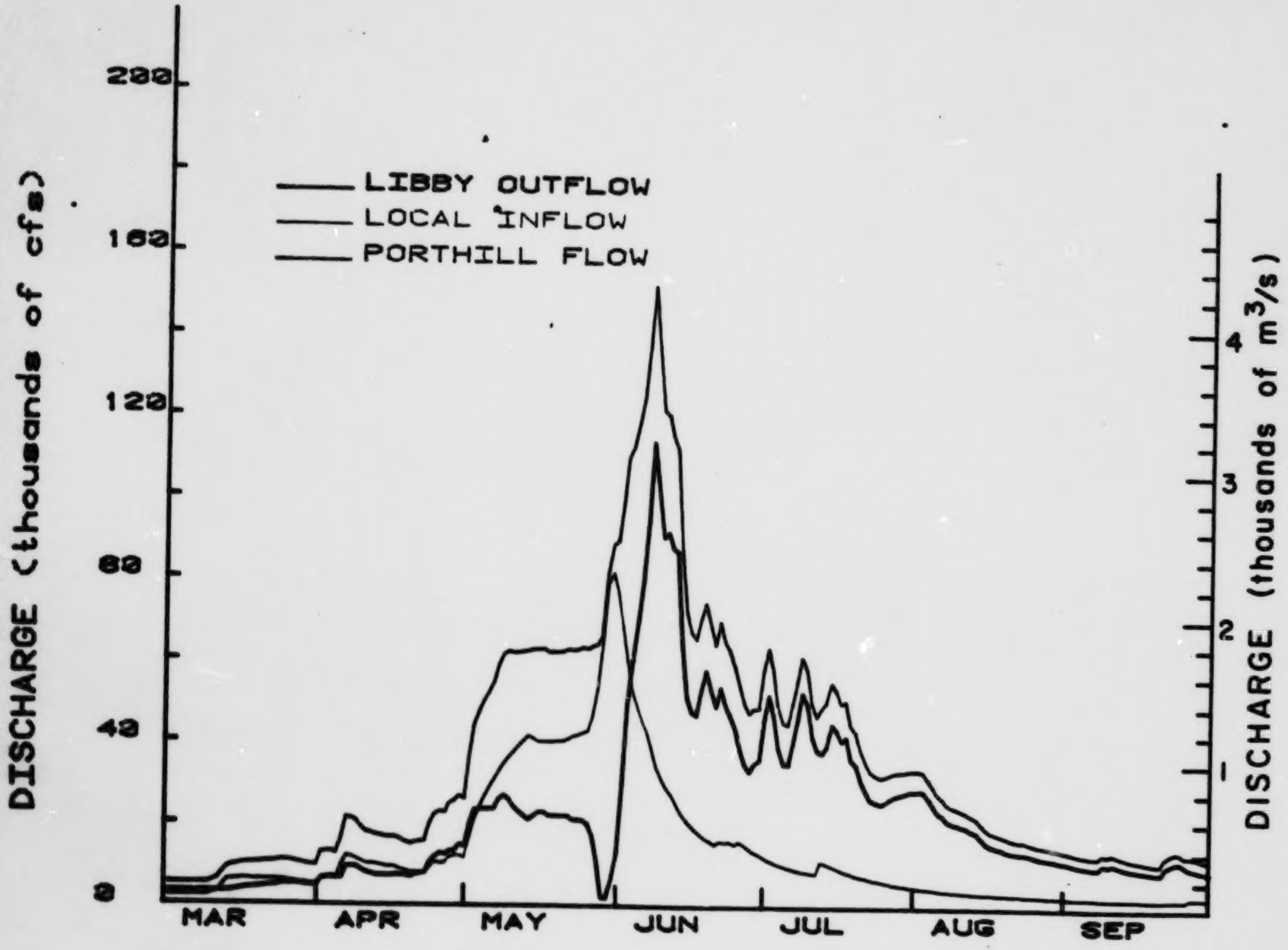


FIGURE 4-9 CONDITIONS AT PORTHILL - 72MY81MY31 (PMUF) SEQUENCE

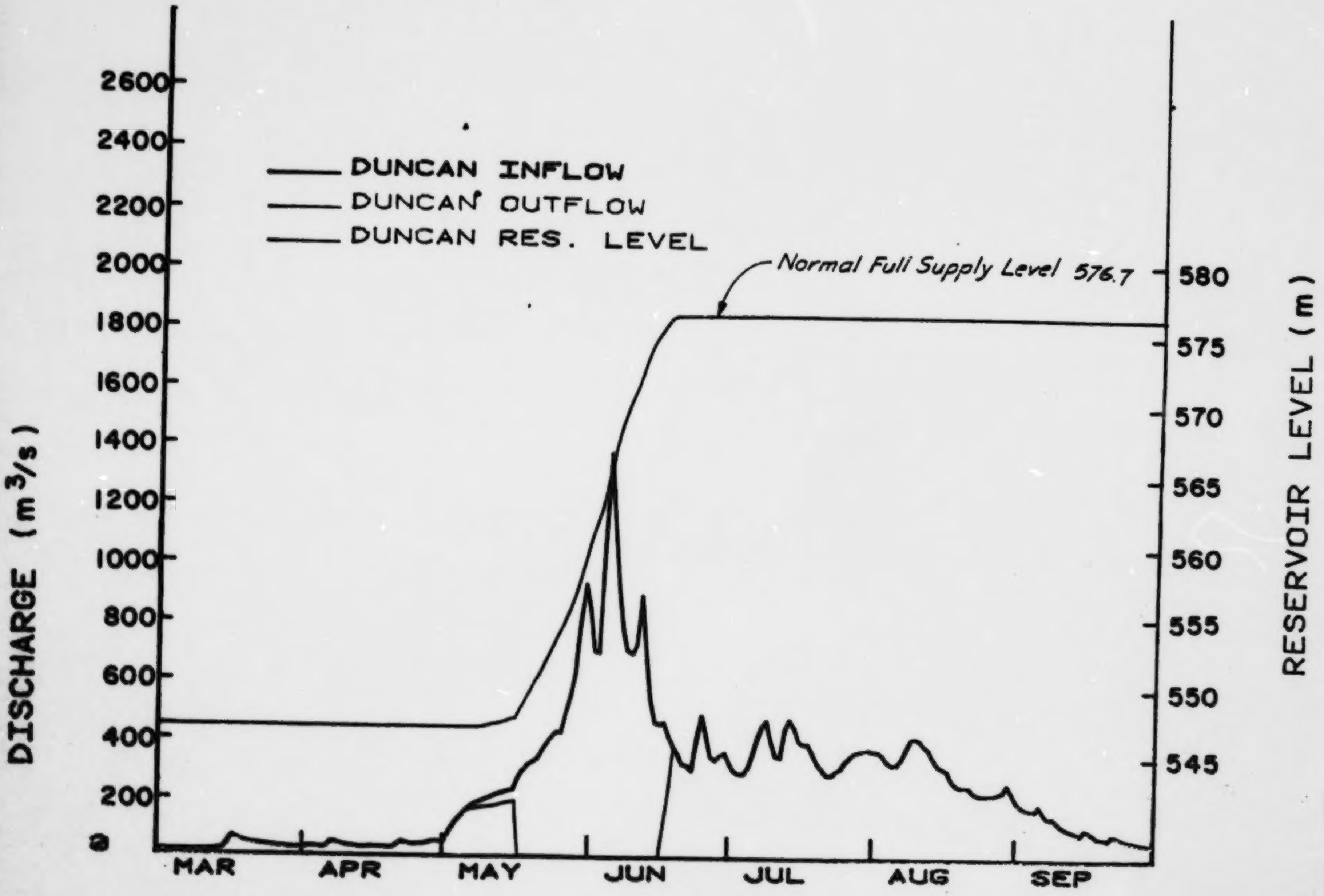


FIGURE 4-10 CONDITIONS AT DUNCAN PROJECT - 72MY81MY31 (PMUF) SEQUENCE

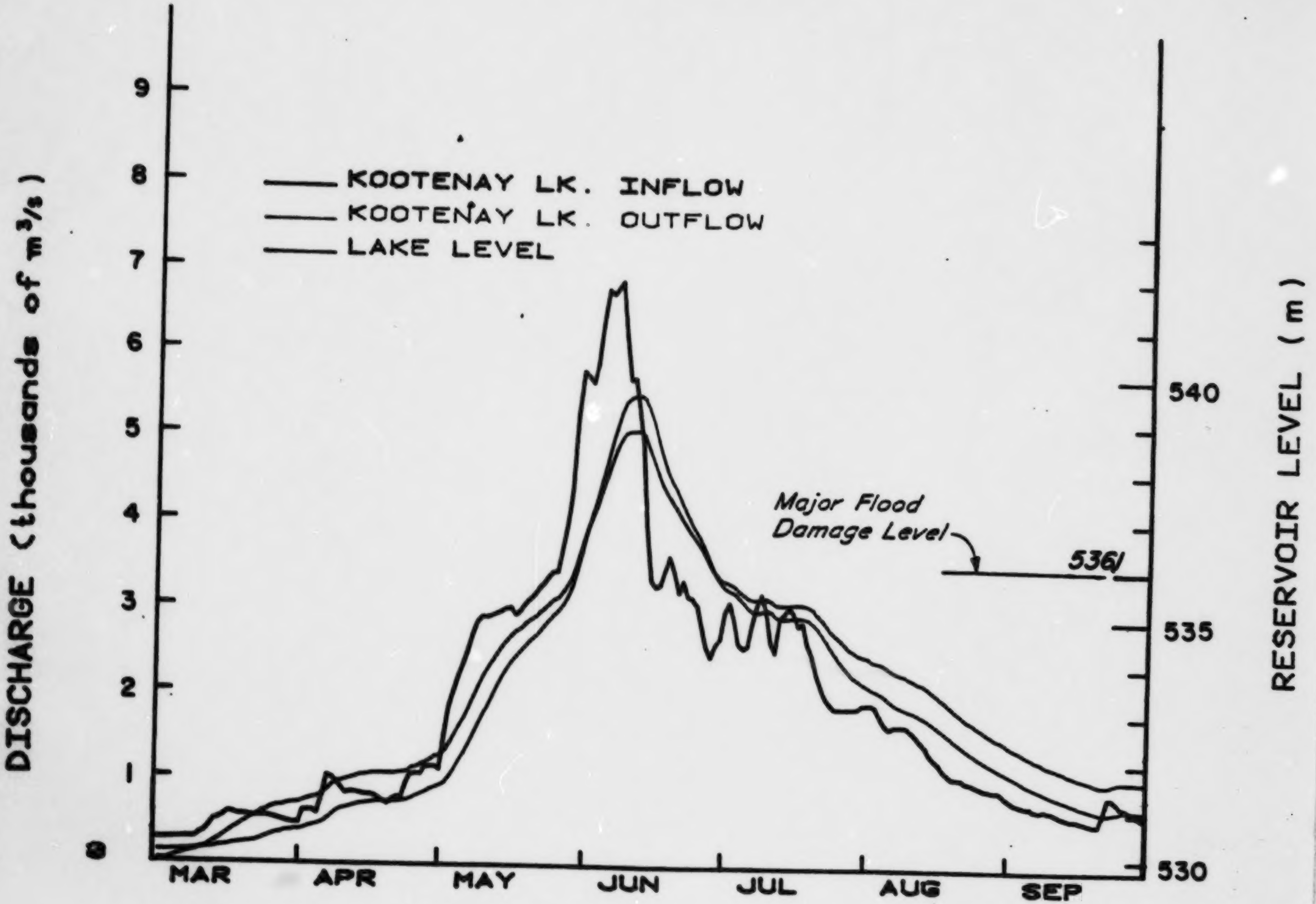


FIGURE 4-11 CONDITIONS AT KOOTENAY LAKE - 72MY81MY31 (PMUF) SEQUENCE

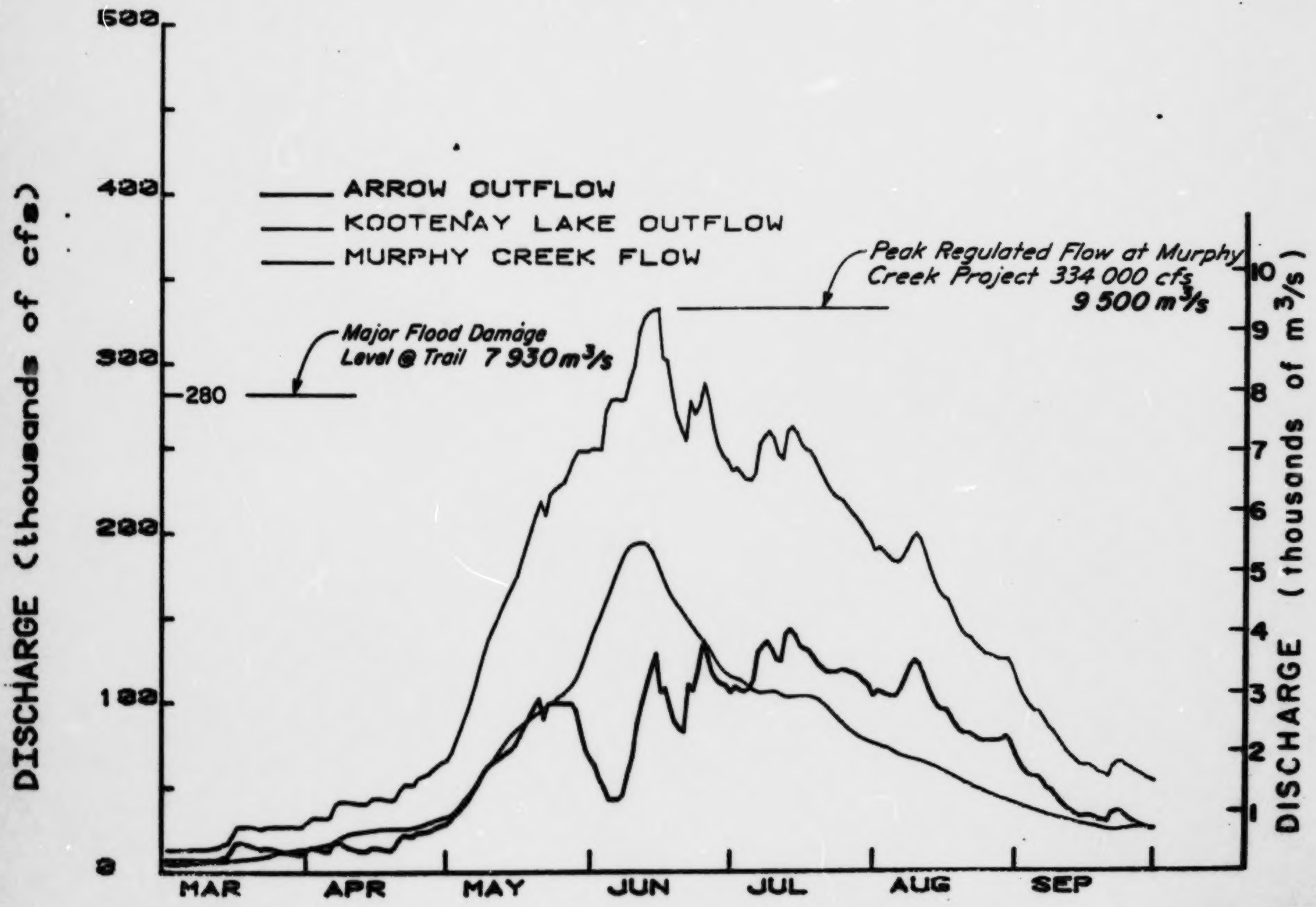


FIGURE 4-12 CONDITIONS AT MURPHY CREEK PROJECT - 72MY01MY31(PMUF)SEQUENCE

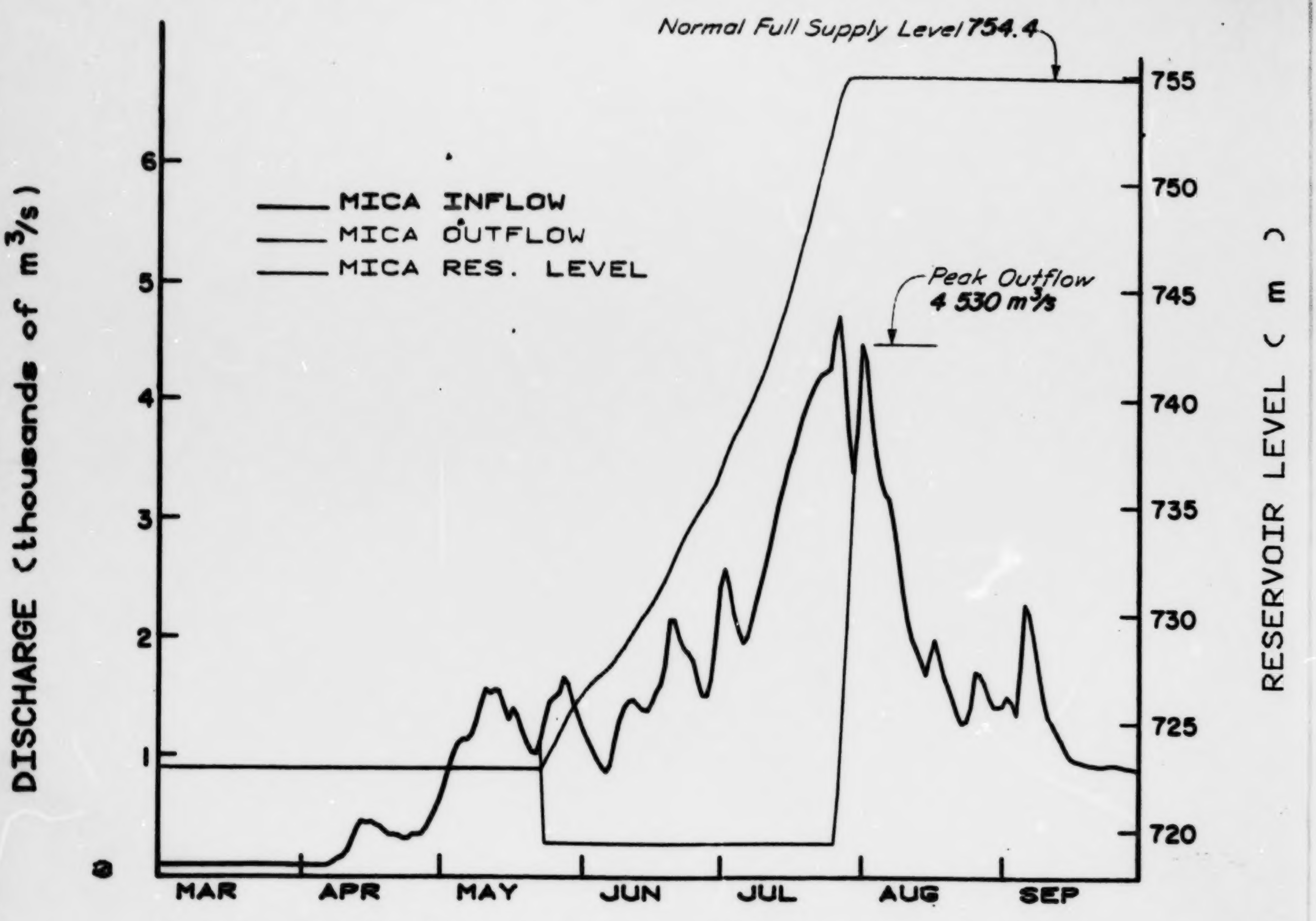


FIGURE 4-13 PMRF CONDITIONS AT MICA PROJECT - 76JL07JL27 SEQUENCE

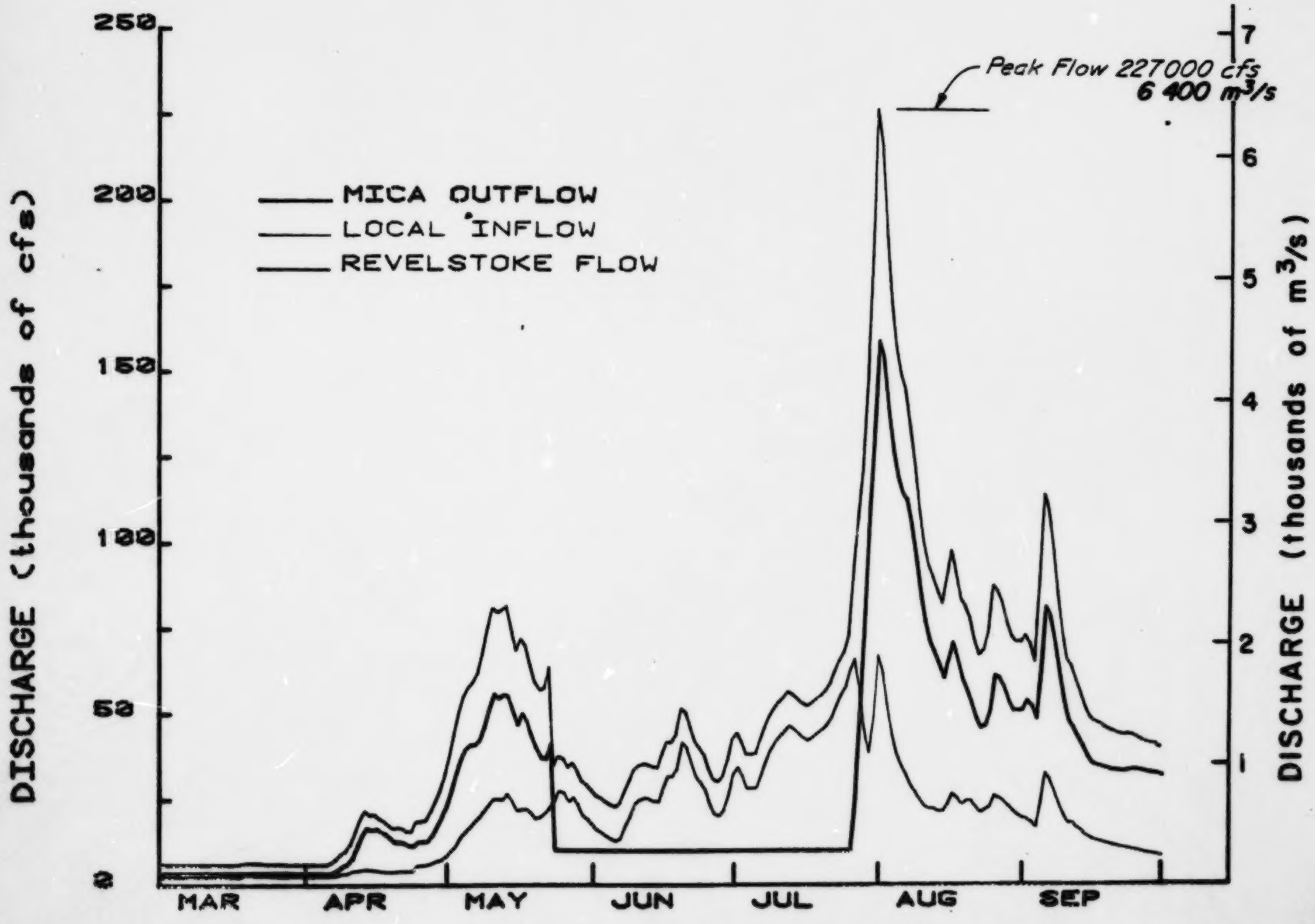


FIGURE 4-14 PMRF CONDITIONS AT REVELSTOKE - 76JL07JL27 SEQUENCE

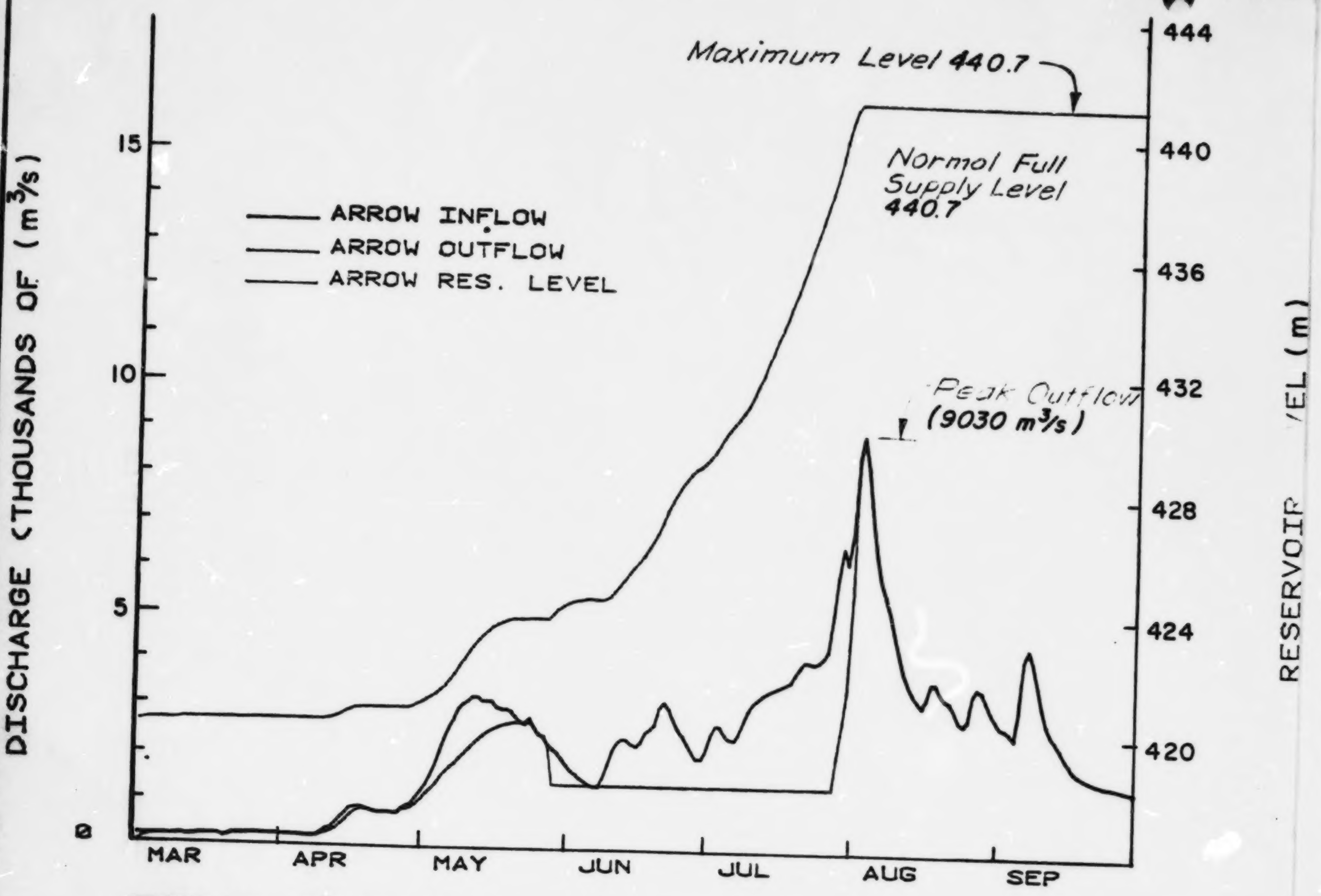


FIGURE 4-15 PMRF CONDITIONS AT ARROW PROJECT - 76JL07JL27 SEQUENCE

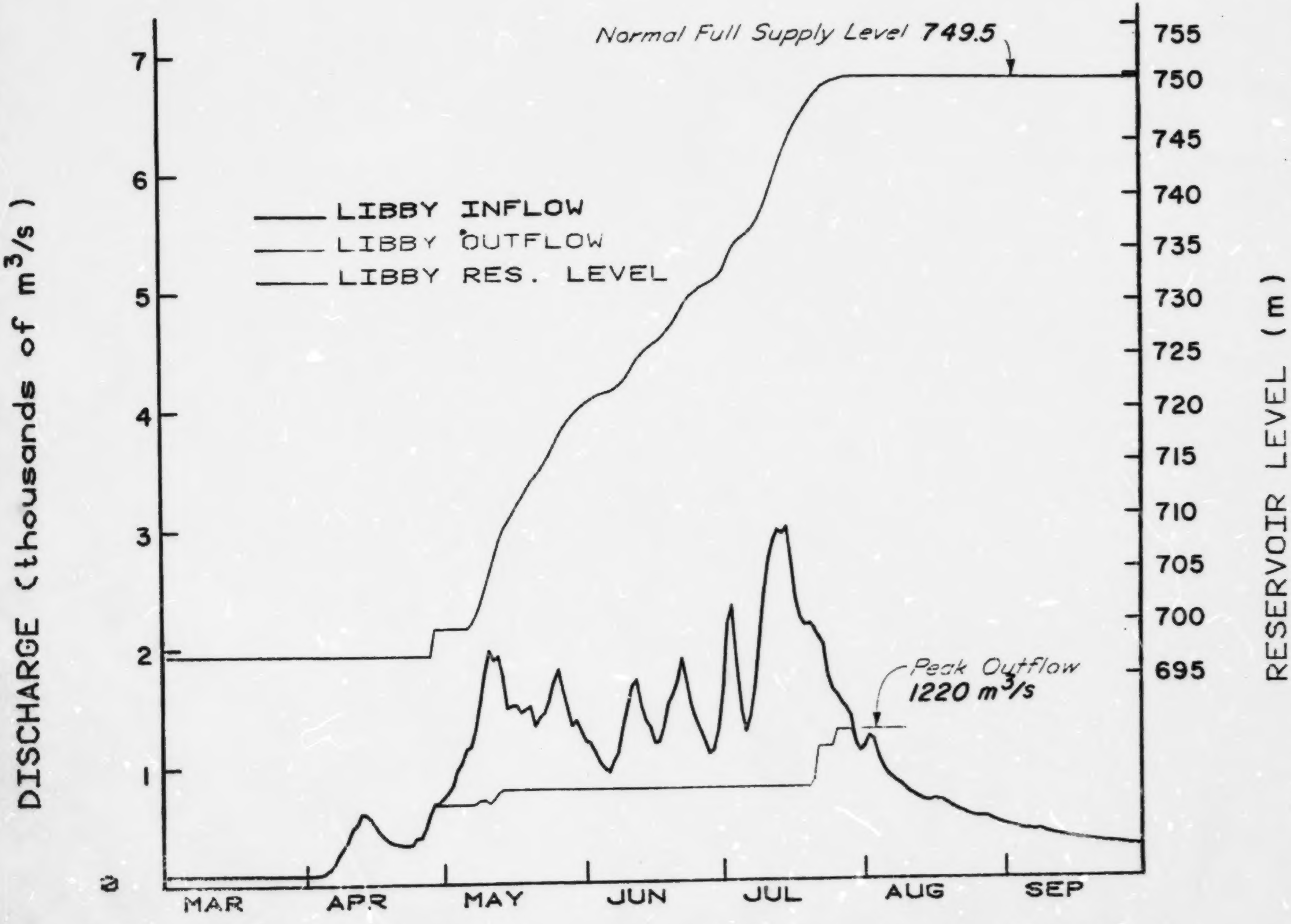


FIGURE 4- 16 PMRF CONDITIONS AT LIBBY PROJECT - 76JL07JL27 SEQUENCE

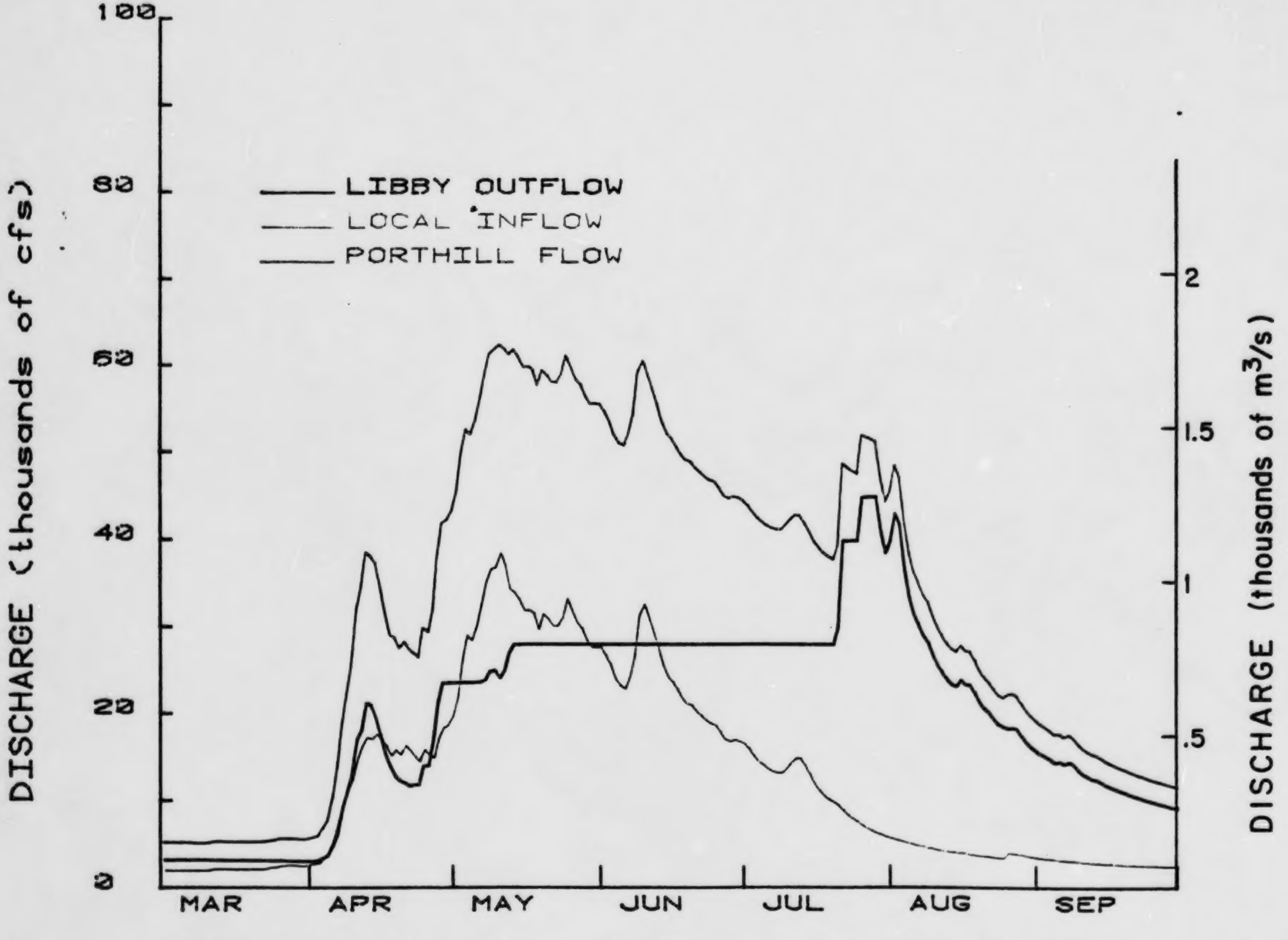


FIGURE 4- 17 PMRF CONDITIONS AT PORTHILL - 76JL07JL27 SEQUENCE

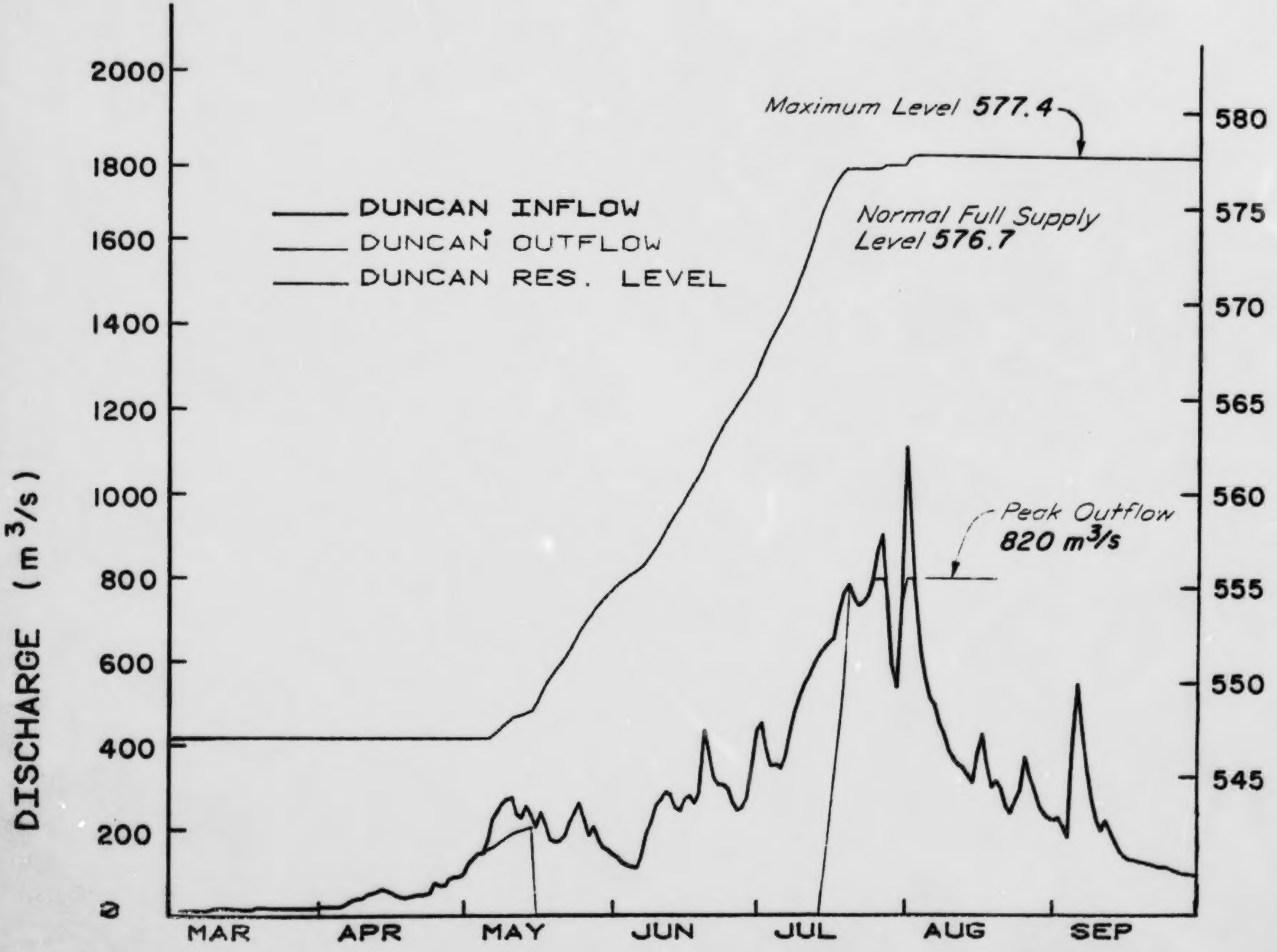


FIGURE 4-18 PMRF CONDITIONS AT DUNCAN PROJECT - 76JL07JL27 SEQUENCE

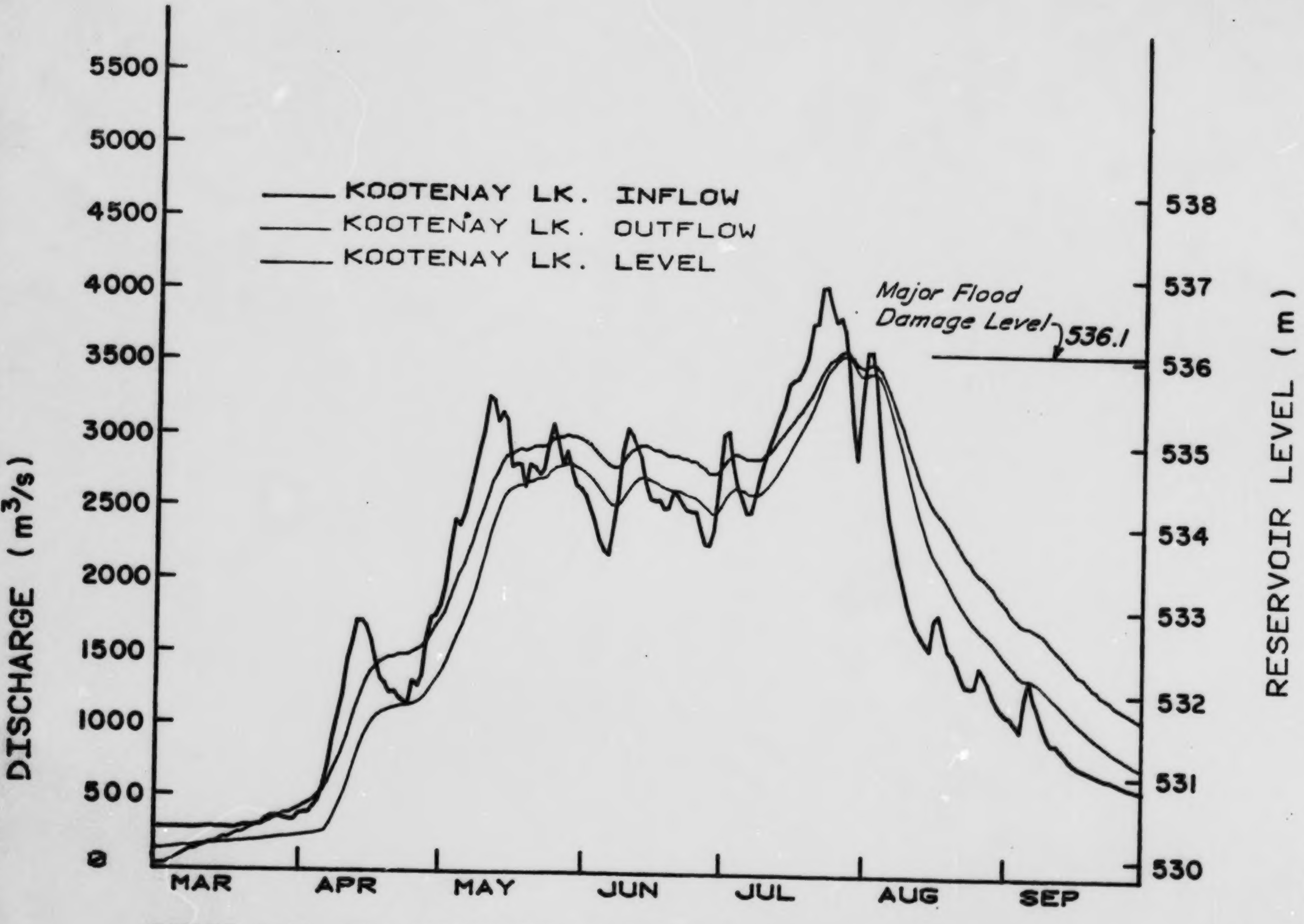


FIGURE 4-19 PMRF CONDITIONS AT KOOTENAY LAKE - 78JL07JL27 SEQUENCE

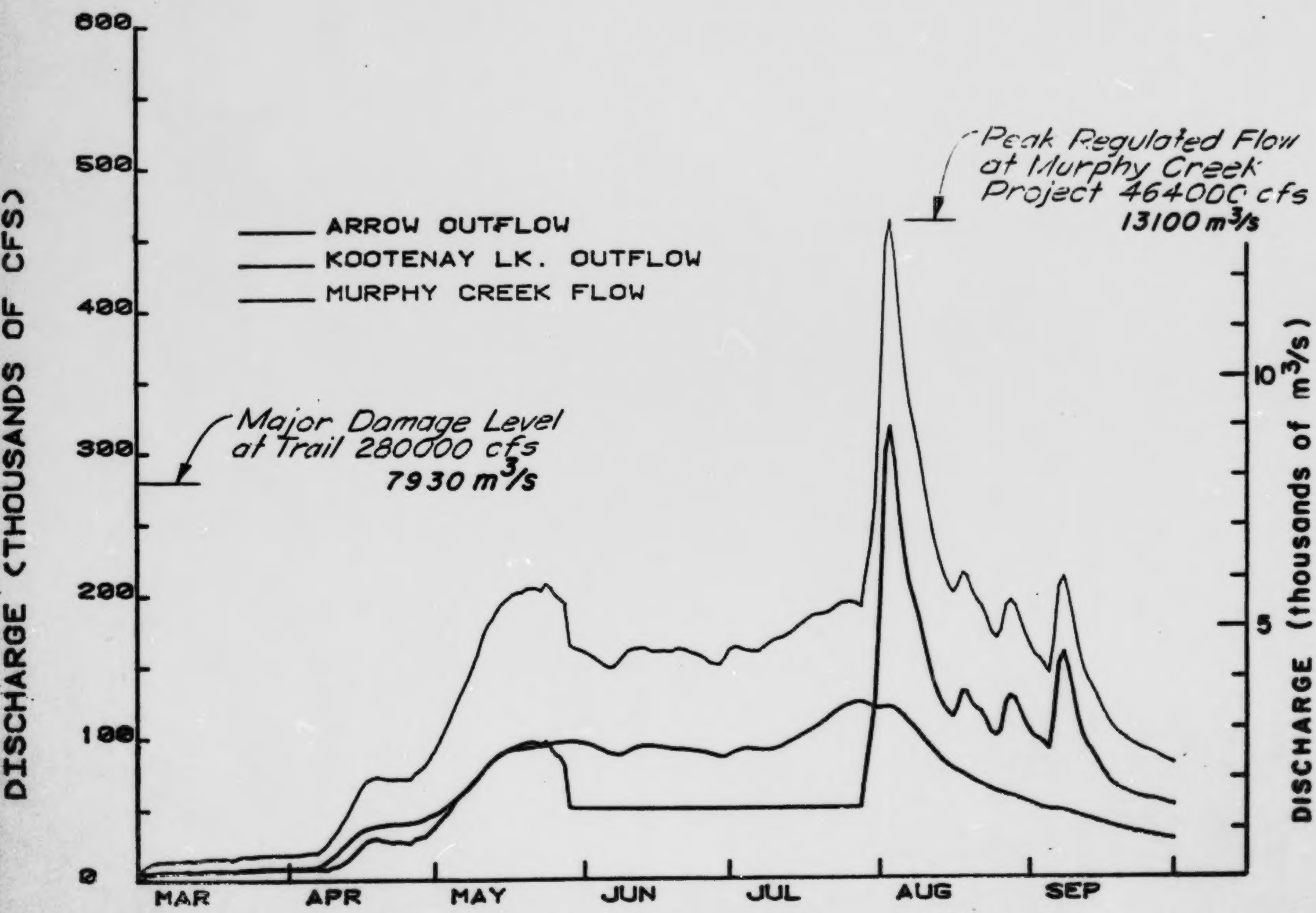


FIGURE 4-20 PMRF CONDITIONS AT MURPHY CREEK PROJECT - 76JL07JL27 SEQUENCE

APPENDIX A

COLUMBIA RIVER TREATY PROJECT DATA

APPENDIX A

COLUMBIA RIVER TREATY PROJECT DATA

CONTENTS

Section	Subject	Page
A.1	PROJECT DESIGN SPECIFICATIONS	A - 1
A.2	NOMINAL DISCHARGE CAPACITY RATINGS - HYDRAULIC STRUCTURES	A - 1

TABLES

Table No.	
A-1	Description of the Mica Project
A-2	Description of the Revelstoke Project
A-3	Description of the Arrow Project
A-4	Description of the Duncan Project
A-5	Description of the Libby Project
A-6	Nominal Discharge Capacity Ratings, Columbia River Treaty Projects, Hydraulic Structures

APPENDIX A
COLUMBIA RIVER TREATY PROJECT DATA

A.1 PROJECT DESIGN SPECIFICATIONS

Supplementary information on the Columbia River Treaty projects is provided in this appendix. The design details of the Columbia River Treaty projects (Mica, Revelstoke, Arrow, Duncan, Libby) upstream of the proposed Murphy Creek project are given in Tables C-1 to C-5. These tables summarize the construction schedule, the storage capacity of the reservoir and construction details of the dam, the hydraulic structures and the power facilities for each project.

A.2 NOMINAL DISCHARGE CAPACITY RATINGS - HYDRAULIC STRUCTURES

The Operations Division of B.C. Hydro and Power Authority supplied data to the study giving the hydraulic capacities of the facilities that would be used to regulate the floods in the Columbia River basin upstream of the Murphy Creek project. These hydraulic capacities were specified as inputs to the UBC Flow Model for the regulation analyses and are summarized in Table C-6.

The equations that were used in the computer model evaluations of the flood control capability of the Columbia Treaty projects are given below. For each equation, "Q" defines the discharge capacity (m^3/s) at the reservoir elevation "E" (metres above sea level).

1. Mica Project

   a. Turbine capacity per unit:

$$\begin{aligned} Q &= 254 + 0.92^{*} (E-707) \text{ for } 741 > E \geq 707 \\ Q &= 285 + 0.69^{*} (E-741) \quad E \geq 741 \end{aligned} \qquad \text{Eqn. M-1}$$

   Note: *Multiply by

b. Outlets:

$Q = 430 + 11.98^{*} (E-707)$ for $737 > E \geq 707$ Eqn. M-2
$Q = 796 + 10.68^{*} (E-737)$ $E \geq 737$

c. Spillway:

$Q = 142.42^{*} (E-742)$ for $747 > E \geq 742$
$Q = 651 + 291.06^{*} (E-747)$ $751 > E \geq 747$ Eqn. M-3
$Q = 1982 + 371.61^{*} (E-751)$ $E \geq 751$

2. Arrow Project

a. Sluice gate (spillway):

$Q = 163.97^{*} (E-425)$ for $427 > E \geq 425$
$Q = 340 + 325.16^{*} (E-427)$ $429 > E \geq 427$ Eqn. A-1
$Q = 1133 + 475.66^{*} (E-429)$ $434 > E \geq 429$
$Q = 3540 + 655.43^{*} (E-434)$ $E \geq 434$

b. Total capacity of eight ports:

$Q = 1347.09^{*} (E-420)$ $421 > E \geq 420$
$Q = 1642 + 474.27^{*} (E-421)$ $424 > E \geq 421$ Eqn. A-2
$Q = 3030 \quad 409.24^{*} (E-424)$ $427 > E \geq 424$
$Q = 4092$ $E \geq 427$

3. Duncan Project

a. Gated tunnels:

$Q = 37.16^{*} (E-543)$ for $553 > E \geq 543$
$Q = 399 + 27.87^{*} (E-553)$ $562 > E \geq 553$ Eqn. D-1
$Q = 651 + 16.16^{*} (E-562)$ $571 > E \geq 562$
$Q = 784 + 5.85^{*} (E-571)$ $E \geq 571$

b. Spillway:

The operation of the spillway was not considered.

4. Libby Project

a. Turbine capacity per unit:

$Q = 105 + 1.22^{*} (E-701)$ for $738 > E \geq 701$
$Q = 150$ $747 > E \geq 738$ Eqn. L-1
$Q = 150 - 1.28^{*} (E-747)$ $E \geq 747$

Note: *Multiply by

b. Sluice gates (low-level):

$$\begin{aligned} Q &= 609 + 12.54^{*}(E-695) && \text{for } 717 > E \geq 695 \\ Q &= 886 + 7.32^{*}(E-717) && 733 > E \geq 717 && \text{Eqn. L-2} \\ Q &= 1002 - 18.39^{*}(E-733) && E \geq 733 \end{aligned}$$

c. Spillway:

$$\begin{aligned} Q &= 139.35^{*}(E-733) && \text{for } 739 > E \geq 733 \\ Q &= 850 + 288.00^{*}(E-739) && 747 > E \geq 739 && \text{Eqn. L-3} \\ Q &= 3115 + 399.48^{*}(E-747) && E \geq 747 \end{aligned}$$

Note: *Multiply by

TABLE A-1

DESCRIPTION OF THE MICA PROJECT

Mica Dam and Kinbasket Lake

Storage	
Construction began	September 1965
Storage became fully operational	29 March 1973
Reservoir	
Normal Full Pool Elevation	754.4 m
Normal Minimum Pool Elevation	707.1 m
Surface Area at Full Pool	43 000 ha
Total Storage Capacity	$25 \times 10^9 m^3$
Usable Storage Capacity	
Total	$15 \times 10^9 m^3$
Commitment to Treaty	$8.6 \times 10^9 m^3$
Dam, Earthfill	
Crest Elevation	760 m
Length	790 m
Approximate height above foundation	240 m
Spillway - Maximum Capacity	$4250 m^3/s$
Outlet Works - Maximum Capacity	$1060 m^3/s$
Power Facilities	
Designed ultimate installation 6 units at 434 MW	2604 MW
Power commercially available	December 1976
Presently installed 4 units at 434 MW	1736 MW
Head at full pool	180 m
Maximum Turbine Discharge of 4 units at full pool	$1080 m^3/s$

TABLE A-2

DESCRIPTION OF THE REVELSTOKE PROJECT

1. Dam	
- Height	150 m
- Crest length	460 m
- Crest elevation	578 m
- Normal minimum freeboard	5 m
2. Earthfill Embankment	
- Height from bedrock	107 m
- Height from riverbed	85 m
- Crest length	1160 m
- Crest elevation	582 m
3. Reservoir	
- Length	130 km
- Area	11 500 ha
- Total storage	$5.3 \times 10^9 m^3$
- Live storage	$1.5 \times 10^9 m^3$
- Normal full elevation	573 m
- Normal operational fluctuation	1.5 m
- Maximum emergency drawdown	15 m
- Maximum flood elevation	574 m
4. Diversion Tunnel	
- Number	1
- Diameter (concrete lined)	13 m
- Length	550 m
- Flow capacity	2400 m^3/s
- Type of gates	Vertical lift
- Number of gates	2
5. Spillway	
- Capacity	4400 m^3/s
- Number of gates	2
- Type of gates	Radial
- Height of gate	17 m
- Width	14 m
- Elevation of gate sills	556 m

TABLE A-2 - (Cont'd)

6.	Power Intakes	
-	Total capacity	2460 m³/s
-	Number of intakes	6
-	Type of gates	Vertical fixed wheel
-	Elevation of sills	542 m
7.	Intermediate Level Outlet	
-	Capacity	2500 m³/s
-	Elevation of sill	518 m
-	Type of gate	Radial
-	Number of gates	2
-	Width of gates	5 m
-	Height of gates	8 m
8.	Penstocks	
-	Number	6
-	Inside diameter steel lined upper end	7.9 m
-	Flow velocity (at full gate output)	8.2 m/s
9.	Powerhouse	
-	Ultimate number of units	6
-	Width	24 m
-	Length machine hall	160 m
-	Length service bay	53 m
	TRAVELLING BRIDGE CRANES	
-	Number	2
-	Capacity of each	500 t
-	Capacity coupled	1000 t
	TURBINES	
-	Type	Francis
-	Number in initial installation	4
-	Net head	127 m
-	Rated output (each)	467 MW
-	Discharge	410 m³/s
-	Runner diameter	7 m
	GENERATORS	
-	Type	Umbrella
-	Synchronous speed	112.5 rpm
-	Rated capacity (PF 95)	460 MW
-	Full plant capacity	2700 MW

TABLE A-2 - (Cont'd)

10. General

-	Excavation rock	2 220 000 m^3
	overburden	7 340 000 m^3
-	Fill	12 230 000 m^3
-	Mass concrete	1 680 000 m^3
-	Structural concrete	214 000 m^3
-	Reinforcing steel	17 000 t
-	Structural steel	6 800 t

TABLE A-3

DESCRIPTION OF THE ARROW PROJECT

Hugh Keenleyside Dam and Arrow Lakes Reservoir

Storage Project	
Construction began	March 1965
Storage became fully operational	10 October 1968
Reservoir	
Normal Full Pool Elevation	440.1 m
Normal Minimum Pool Elevation	420.0 m
Surface Area at Full Pool	52 600 ha
Total Storage Capacity	$10.3 \times 10^9 m^3$
Usable Storage Capacity	$8.7 \times 10^9 m^3$
Treaty Storage Commitment	$8.7 \times 10^9 m^3$
Dam, Concrete Gravity and Earthfill	
Crest Elevation	444.7 m
Length	870 m
Approximate height above riverbed	52 m
Spillway - Maximum Capacity	6800 m^3/s
Low Level Outlets - Maximum Capacity	3700 m^3/s
Power Facilities	
None	

TABLE A-4

DESCRIPTION OF THE DUNCAN PROJECT

Duncan Dam and Duncan Lake

Storage Project	
Construction began	17 September 1964
Storage became fully operational	31 July 1967
Reservoir	
Normal Full Pool Elevation	576.7 m
Normal Minimum Pool Elevation	546.9 m
Surface Area at Full Pool	7300 ha
Total Storage Capacity	$1.8 \times 10^9 m^3$
Usable Storage Capacity	$1.7 \times 10^9 m^3$
Treaty Storage Commitment	$1.7 \times 10^9 m^3$
Dam, Earthfill	
Crest Elevation	581.3 m
Length	790 m
Approximate height above riverbed	40 m
Spillway - Maximum Capacity	1350 m^3/s
Discharge Tunnels - Maximum Capacity*[1]	570 m^3/s
Power Facilities	
None	

---

*[1] BCHPA Operations Control Department has found that the discharge tunnels have a capacity of 820 m^3/s.

TABLE A-5

DESCRIPTION OF THE LIBBY PROJECT

Libby Dam and Lake Koocanusa

Storage Project	
Construction began	1966
Storage became fully operational	17 April 1973
Reservoir	
Normal Full Pool Elevation	749.5 m
Normal Minimum Pool Elevation	697.1 m
Surface Area at Full Pool	18 800 ha
Total Storage Capacity	$7.2 \times 10^9 m^3$
Usable Storage Capacity	$6.1 \times 10^9 m^3$
Dam, Concrete Gravity	
Deck Elevation	753.5 m
Length	930 m
Approximate height above riverbed	113 m
Spillway - Maximum Capacity	4100 m^3/s
Low Level Outlets - Maximum Capacity	1700 m^3/s
Power Facilities	
Designed ultimate installation 8 units at 105 MW	840 MW
Power commercially available	24 August 1975
Presently installed 4 units at 105 MW	420 MW
Head at full pool	107 m
Maximum Turbine Discharge of 4 units at full pool	560 m^3/s

TABLE A-6

NOMINAL DISCHARGE CAPACITY RATINGS
COLUMBIA RIVER TREATY PROJECTS - HYDRAULIC STRUCTURES

		Discharge Capacity at FSL (m^3/s)[*1]						
Project Name	Normal Full Supply Level (FSL) (m)	Turbines[*2]	High Level Outlet	Sluice Gates	Ports	Gated Tunnel	Spillway	Total
Mica	754.4	1 180	960	-	-	-	3 100	5 270
Arrow	440.1	-	-	7 300	3 200	-	-	10 500[*2]
Duncan	576.7	-	-	-	-	820	(1 200)	820[*3]
Libby	749.5	590	-	700	-	-	4 200	5 490

[*1] Tables A1 to A5 give the design capacity of the Treaty project hydraulic structures. Capacity ratings given in this table are based on field test results, and these capacity ratings were used in the flood regulation studies.

[*2] The Columbia River Treaty requires that the discharge capacity provided for flood control operations be evaluated on the basis of the full use of any conduits provided for that purpose plus one half of the hydraulic capacity of the turbine installation at the time of commencement of the operation of storage under the Treaty.

[*3] Regulation of flood flows were based on the use of the gated tunnels; the use of the spillway was not required for the regulation of the extreme floods considered in the derivation of the Probable Maximum Regulated Flood for the Murphy Creek project.

APPENDIX B

UBC WATERSHED MODEL PARAMETER SPECIFICATIONS

APPENDIX B

UBC WATERSHED MODEL PARAMETER SPECIFICATIONS

CONTENTS

Section	Subject	Page
B.1	Columbia River Basin Calibrations	B - 1

TABLES

Table No.	
B-1	UBC Watershed Model Calibration Parameters - Donald Sub-basin
B-2	UBC Watershed Model Calibration Parameters - Mica Local Sub-basin
B-3	UBC Watershed Model Calibration Parameters - Revelstoke Local Sub-basin
B-4	UBC Watershed Model Calibration Parameters - Upper Arrow Local Sub-basin
B-5	UBC Watershed Model Calibration Parameters - Lower Arrow Local Sub-basin
B-6	UBC Watershed Model Calibration Parameters - Fort Steele Sub-basin
B-7	UBC Watershed Model Calibration Parameters - Libby Local Sub-basin
B-8	UBC Watershed Model Calibration Parameters - Porthill Local Sub-basin
B-9	UBC Watershed Model Calibration Parameters - Duncan Sub-basin
B-10	UBC Watershed Model Calibration Parameters - Kootenay Lake Local Sub-basin
B-11	UBC Watershed Model Calibration Parameters - Slocan Sub-basin
B-12	UBC Watershed Model Calibration Parameters - Birchbank Local Sub-basin

APPENDIX B
UBC WATERSHED MODEL PARAMETER SPECIFICATIONS

B.1 COLUMBIA RIVER BASIN CALIBRATIONS

The flood runoff in the Columbia River drainage basin upstream of the Murphy Creek project site was evaluated separately in each of 12 subareas in the watershed shown in Fig. 3-1. The final calibration parameters used in the derivation of the Probable Maximum Flood for the proposed Murphy Creek project are given in Tables B-1 to B-12. The glossary of terms and further explanations concerning the structure and use of the model are given in the "UBC Watershed Model - User's Manual", by A. Pipes and M.C. Quick, Department of Civil Engineering, University of British Columbia, April 1977.

```
: ............ HYDROLOGIC  ANALYSIS  PROGRAM  :
: .......  UBC  WATERSHED  MODEL  (DEC 1976)  :
: ............................ JOB  REFERENCE  :
                              INPUT  # 1   ..YEAR;PTHEAD;
                                           1964. COL & DONA  R03 OJD   : GOL &  G8P THU DEC 20 11.04
: ....................... EXECUTION  CONTROL  :
                              INPUT  # 2   NMONTH;MSTART;....NY;....MO;....DY;..ILAK;IAGLAC;IRADAT;ISHORE;
                                            160     12      2     10     31      0      1      0      0
: ................ WATERSHED  REPRESENTATION  :
                              INPUT  # 3   (ELL(L),L=1,NB);
                                            1500.  2500.  3500.  4500.  5500.  6500.  7500.  8500.  9500. 10500.
                              INPUT  # 4   (A(L),L=1,NB);
                                             0.0  407.00 567.00 509.00 545.00 673.00 590.00 281.00  86.00  41.00
                              INPUT  # 5   (AG(L),L=1,NB);
                                             0.0    0.0    0.0    0.0    0.0    0.0    0.0 225.00  76.00  41.00
                              INPUT  # 6   ..ALAK;STAREA;
                                             0.0    0.0
: ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                              INPUT  # 7   (EL(I),I=1,NS);
                                            2583.  4340.
: .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 8   ELLXPL;ELLXPU;ELHORO;STABIF;TRFORM;LOWPSI;NSGNLY;NSLYSD;NSLYST;
                                            4000. 20000.  3750. 0.0055   15.0     3      0      1     12
                              INPUT  # 9   (SHOREP(I),I=1,NS);(RANREP(I),I=1,NS);
                                            -0.50  -0.65  -0.10  -0.25
: .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 10  TZLAPS;NSLAPS;NSBASE;IVALYT;TRNREP;TRNLOC;
                                             3.3    -1      0      1    64.    64.
: ........ SNOWMELT  CALCULATION  PARAMETERS  :
                              INPUT  # 11  PTSMLT;XTDEMP;XTDIUM;XTCEMX;ANMLTF;IMLTFM;IWEDGE;.ZENCH;..ZALB;
                                             4.5    70.     2.    1.0   0.96     10     -1    0.0    0.0
: .......... RUNOFF  CALCULATION  PARAMETERS  :
                              INPUT  # 12  AETGEN;DELAEG;.HXIMP;DELMXP;AREGEN;
                                             600.   100.   0.01   0.0    600.
                              INPUT  # 13  GWPERC;BZSHRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IDEUPS;BISHRE;IABSTR;
                                             20.   0.00   0.10999999.     4   0.15      0    0.0      1
                              INPUT  # 14  (ABSMAX(L),L=1,NB);
                                             200.   250.   400.   700.   800.  1000.  1200.  1500.  1800.  1800.
                              INPUT  # 15  (ABSSTK(L),L=1,NB);
                                           0.2000 0.2000 0.1000 0.0400 0.0400 0.0400 0.0400 0.0400 0.0400 0.0400
: ........... WATERSHED  ROUTING  PARAMETERS  :
                              INPUT  # 16  ...NUM;NRESVD;UNHYSK;UTRFLD;INTSTK;...LAG;
                                              10     2.    3.0    0.0   1.00      1
                              INPUT  # 17  UGWSTK;DZWSTK;LAGBAS;UPSSTK;SURSTK;
                                            0.030 0.0020      0  0.030  0.030
: ......... WATERSHED  STATE  INITIALIZATION  :
                              INPUT  # 18  (SNOPAK(L),L=1,NB);
                                             300.   400.   600.   750.  1400.  2000.  2100.  2200.  2300.  2300.
                              INPUT  # 19  (SOILDF(L),L=1,NB);
                                             900.   300.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 20  (INTFLD(L),L=1,NB);
                                               0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 21  BASFLO;IDZBAS;UPSTOR;SUSTOR;
                                            1200.      1     0.     0.
                              INPUT  # 22  (ABSTOR(1,L),L=1,NB);
                                               0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
: ............... GRAPHICAL  OUTPUT  CONTROL  :
                              INPUT  # 23  HGRAPH;PJSCAL;PHSCAL;GRAFGO;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS;
                                               1.   100. 50000.     1.     7.    -1.   100.   250.    -1.
            .... PRINTED  OUTPUT  CONTROL  :
                              INPUT  # 24  NDAILS;MAKEUP;MAKUP2;MAKUPG;
                                              -1      0      0      0
```

TABLE B-1 - UBC WATERSHED MODEL CALIBRATION
PARAMETERS - DONALD SUB-BASIN

```
: ............ HYDROLOGIC  ANALYSIS  PROGRAM  :
: ....... UBC  WATERSHED  MODEL  (DEC 1976)  :
: ........................... JOB  REFERENCE  :
                              INPUT  #  1   ..YEAR;PTHEAD;
                                             1964. MICA RES -DOH R02 8JD  (VALDOL GRP THU DEC 28 12.09
: ....................... EXECUTION  CONTROL  :
                              INPUT  #  2   NMONTH;MSTART;....NS;....NB;....ND;..ILAK;IAGLAC;IRADAT;ISNOBE;
                                              160    12     2    10    31     0     1     0     0
: ................ WATERSHED  REPRESENTATION  :
                              INPUT  #  3   (ELL(L),L=1,NB);
                                             1500.  2500.  3500.  4500.  5500.  6500.  7500.  8500.  9500. 10500.
                              INPUT  #  4   (A(L),L=1,NB);
                                              0.0  361.00 600.00 643.00 642.00 644.00 602.00 535.00 335.00 180.00
                              INPUT  #  5   (AG(L),L=1,NB);
                                              0.0    0.0    0.0    0.0    0.0    0.0   50.00 200.00 300.00 180.00
                              INPUT  #  6   ..ALAK;STAREA;
                                              0.0    0.0
: ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                              INPUT  #  7   (EL(I),I=1,NS);
                                             2615.  4340.
: .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                              INPUT  #  8   ELLXPL;ELLXPU;ELMOBO;STABIF;TRFORM;LOUPSI;NSONLY;NBLYBO;NBLYST;
                                             4000. 20000.  3750. 0.0050   35.0     1     0     1    12
                              INPUT  #  9   (SNOREP(I),I=1,NS);(RAHREP(I),I=1,NS);
                                              0.10  -0.25   0.25   0.15
: .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 10   TZLAPS;HBLAPS;HSBASE;IVALTT;TRNREP;TRNLOC;
                                               3.3     -1      0      1    64.    64.
: ........ SNOWMELT  CALCULATION  PARAMETERS  :
                              INPUT  # 11   PTSMLT;XTDEMP;XTDIUM;XTCEMK;ANMLTF;IMLTFH;INEDGE;.ZZXCK;..ZALB;
                                               4.5    60.     2.    1.0   0.96     10     -1    0.0    0.0

: .......... RUNOFF  CALCULATION  PARAMETERS  :
                              INPUT  # 12   AETGEN;DELAEG;.MXIMP;DELMMP;AREGEN;
                                              500.   100.   0.05   0.0   600.
                              INPUT  # 13   GWPERC;DZSHRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RIDNRE;IABSTR;
                                               10.   0.99  0.20999999.     7   0.12      0   0.0      1
                              INPUT  # 14   (ABSMAX(L),L=1,NB);
                                              100.   100.   200.   400.   400.   600.  1200.  1200.  1200.  1200.
                              INPUT  # 15   (ABSSTK(L),L=1,NB);
                                             0.2000 0.2000 0.1500 0.0000 0.0300 0.0300 0.0300 0.0300 0.0300 0.0300

: ........... WATERSHED  ROUTING  PARAMETERS  :
                              INPUT  # 16   ...NUH;NRESVO;LAGYDK;UTRFLD;INTSTK;...LAG;
                                                10     2.    1.0    0.0   1.00      0
                              INPUT  # 17   UGWSTK;DZHSTK;LAGBAS;UPSSTK;SURSTK;
                                             0.025 0.0025      0  0.050  0.050
: ......... WATERSHED  STATE  INITIALIZATION  :
                              INPUT  # 18   (SNOPAK(L),L=1,NB);
                                              452.   653.  1540.  2676.  3334.  3930.  3975.  4000.  4000.  4000.
                              INPUT  # 19   (SOILDF(L),L=1,NB);
                                                0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 20   (INTFLS(L),L=1,NB);
                                                0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 21   BASFLO;IDZBAS;UPSTOR;SUSTOR;
                                             2436.      1     0.     0.
                              INPUT  # 22   (ABSTOR(1,L),L=1,NB);
                                                0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

: ............... GRAPHICAL  OUTPUT  CONTROL  :
                              INPUT  # 23   NGRAPH;PJSCAL;PHSCAL;GRAFGO;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS;
                                                1.  100.100000.    1.     7.    -1.   100.   250.    -1.

: ........... PRINTER  OUTPUT  CONTROL  :
                              INPUT  # 24   NDAILS,MAKEUP;MAKUP2;MAKUPG;
                                                -1      0      0      0
```

TABLE B-2 - UBC WATERSHED MODEL CALIBRATION PARAMETERS - MICA LOCAL SUB-BASIN

```
: ............ HYDROLOGIC ANALYSIS PROGRAM :
: ....... UBC WATERSHED MODEL (DEC 1976) :
: ............................ JOB REFERENCE :
                              INPUT 0 1   ..YEAR;PTHEAD;
                                           1964. UREV 000 - MAG DJB 002: DEVBGN GRP THU DEC 20 12.23
: ....................... EXECUTION CONTROL :
                              INPUT 0 2   NMONTH;MSTART;....NB;....ND;....ND;..ILAK;IAGLAC;IRADAT;ISNOBE;
                                            168    12     2    10    31     0     1     0     0
: ............... WATERSHED REPRESENTATION :
                              INPUT 0 3   (ELL(L),L=1,NB);
                                           1500.  2500.  3500.  4500.  5500.  6500.  7500.  8500.  9500. 10500.
                              INPUT 0 4   (A(L),L=1,NB);
                                           62.00 212.00 270.00 373.00 425.00 423.00 107.00  89.00  27.00  11.00
                              INPUT 0 5   (AG(L),L=1,NB);
                                            0.0    0.0    0.0    0.0    0.0    0.0   25.00  60.00  27.00  11.00
                              INPUT 0 6   ..ALAK;STAREA;
                                            0.0    0.0
: ...... METEOROLOGICAL STATION ELEVATIONS :
                              INPUT 0 7   (EL(I),I=1,NS);
                                           1670.  4340.
: .. PRECIPITATION DISTRIBUTION PARAMETERS :
                              INPUT 0 8   ELLXPL;ELLXPU;ELHORO;STADIF;TRFORM;LOUPSI;NSONLY;NSLYDD;NSLYST;
                                           10000. 30000.  3750. 0.0005  15.0    3     0     1    12
                              INPUT 0 9   (SNOREP(I),I=1,NS);(RAMREP(I),I=1,NS);
                                            0.15  -0.10   0.25   0.25
: .... TEMPERATURE DISTRIBUTION PARAMETERS :
                              INPUT 0 10  TILAPS;NSLAPS;NSBASE;IVALYT;TRNDEP;TDNLOC;
                                            3.3    -1     0     1    64.    64.
: ........ SNOWMELT CALCULATION PARAMETERS :
                              INPUT 0 11  PTSMLT;XTDEWP;XTDIUM;XTCEMX;AMMLTF;INLTFN;INEDGE;.ZEXCN;..ZALD;
                                            4.5    60.     2.    1.0   0.95    10    -1   0.0    0.0
: .......... RUNOFF CALCULATION PARAMETERS :
                              INPUT 0 12  AETGEN;DELAED;.MXIMP;DELMXP;AREBEN;
                                           500.   100.   0.05   0.0   400.
                              INPUT 0 13  GWPERC;DZSHRE;DELDIS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISHRE;IABSTR;
                                            20.   0.99  0.2099999.    10   0.10     0   0.0      1
                              INPUT 0 14  (ABSMAX(L),L=1,NB);
                                           100.   200.   200.   250.   350.  1600.  1000.  1000.  1000.  1000.
                              INPUT 0 15  (ABSSTK(L),L=1,NB);
                                          0.2000 0.2000 0.1500 0.1500 0.0600 0.0600 0.0400 0.0300 0.0300 0.0300
: ........... WATERSHED ROUTING PARAMETERS :
                              INPUT 0 16  ...NGN;NRESVD;UNGVBK;UTBFLD;INTSTK;...LAG;
                                            10     2.    1.6    0.0   1.00     0
                              INPUT 0 17  UGNSTK;DZNSTK;LAGBAS;UPSSTK;BURSTK;
                                           0.030 0.0020     0  0.010  0.010
: ......... WATERSHED STATE INITIALIZATION :
                              INPUT 0 18  (SNOPAK(L),L=1,NB);
                                           1300.  1700.  2500.  2900.  3500.  4200.  4600.  4600.  4600.  4600.
                              INPUT 0 19  (SOILDF(L),L=1,NB);
                                             0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT 0 20  (INTFLS(L),L=1,NB);
                                             0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT 0 21  BASFLO;ISZBAS;UPSTOR;BUSTOR;
                                           2500.     1     0.     0.
                              INPUT 0 22  (ABSTOR(1,L),L=1,NB);
                                             0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
: ............... GRAPHICAL OUTPUT CONTROL :
                              INPUT 0 23  NGRAPH;PJSCAL;PHSCAL;GRAFBD;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS;
                                             1.  180.100000.    1.     7.    -1.   100.   250.    -1.

                              INPUT 0 24  (NAILS;MAXLUP;MAXUP2;MAXUPS;
                                            -1      0      0      0
```

TABLE B-3 - UBC WATERSHED MODEL CALIBRATION PARAMETERS - REVELSTOKE LOCAL SUB-BASIN

```
: ............ HYDROLOGIC ANALYSIS [illegible]
: ....... UBC WATERSHED MODEL (DEC 1976) :
: ......................... JOB REFERENCE :
                          INPUT # 1   ..YEAR;PTHEAD;
                                       1969. ARROW LAKE UPPER RVA & BRP THU DEC 20 1979 10.03

: ..................... EXECUTION CONTROL :
                          INPUT # 2   NMONTH;MSTART;....NB;....NB;....NB;..ILAK;IADLAC;IRABAT;ISNODE;
                                        96    12    2    11    31    0    1    0    0

: ............... WATERSHED REPRESENTATION :
                          INPUT # 3   (ELL(L),L=1,NB);
                                       1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                          INPUT # 4   (A(L),L=1,NB);
                                       336.00 243.00 296.00 368.00 303.00 474.00 422.00 264.00 137.00  55.00  11.00
                          INPUT # 5   (AG(L),L=1,NB);
                                         0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0  40.00  55.00  11.00
                          INPUT # 6   ..ALAK;STAREA;
                                         0.0    0.0

: ...... METEOROLOGICAL STATION ELEVATIONS :
                          INPUT # 7   (EL(I),I=1,NS);
                                       1500.  4340.

: .. PRECIPITATION DISTRIBUTION PARAMETERS :
                          INPUT # 8   ELLXPL;ELLXPU;ELMODO;STADIF;TRPGRM;LOUPSI;NBONLY;NOLYBG;NOLYST;
                                       6000. 30000.  3500. 0.0008   30.0     2     0     1    12
                          INPUT # 9   (SNOREP(I),I=1,NS);(RAMREP(I),I=1,NS);
                                       -0.25   0.0    0.0    0.40

: .... TEMPERATURE DISTRIBUTION PARAMETERS :
                          INPUT # 10  TZLAPS;NSLAPS;NOBASE;IVALYT;TBNREP;TBNLOC;
                                         3.3    -1     0     1   64.   64.

: ....... SNOWMELT CALCULATION PARAMETERS :
                          INPUT # 11  PTSNLT;XTDEMP;XTDIUN;XTCEMX;ANMLTF;INLTFN;IMERGE;.ZZXCH;..ZALB;
                                         4.5   60.    2.   1.0   0.96    11    -1   0.0   0.0

: ......... RUNOFF CALCULATION PARAMETERS :
                          INPUT # 12  ASTGEN;DELAEG;.MKINP;DELUNP;AREGEN;
                                         500.  100.  0.08   0.0   400.
                          INPUT # 13  SNPERC;DZSNRE;DELDZS;UPDMAX;..IUPS;UPSPCR;IREUPS;RISNRE;IABSTR;
                                          25.  0.90  0.40000000.     9  0.50     0   0.0     1
                          INPUT # 14  (ABSMAX(L),L=1,NB);
                                          200.   200.   200.   600.   600.   600.  1000.  1500.  1500.  1500.  1500.
                          INPUT # 15  (ABSSTK(L),L=1,NB);
                                       0.2500 0.2500 0.2500 0.2500 0.2000 0.2000 0.0000 0.0000 0.0000 0.0000 0.0000

: .......... WATERSHED ROUTING PARAMETERS :
                          INPUT # 16  ...NUN;NRESVD;UNITBK;UTRFLO;INTSTK;...LAG;
                                          10    2.   0.9   0.0  1.00     1
                          INPUT # 17  UBASTK;DZNSTK;LAGBAS;UPSSTK;BARSTK;
                                        0.040 0.0020     0 0.100 0.100

: ......... WATERSHED STATE INITIALIZATION :
                          INPUT # 18  (SNOPAK(L),L=1,NB);
                                          900.  1300.  1800.  2400.  3000.  3400.  3600.  3700.  4000.  4000.  4000.
                          INPUT # 19  (SOILDF(L),L=1,NB);
                                           0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                          INPUT # 20  (INTFLO(L),L=1,NB);
                                           0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                          INPUT # 21  BASFLO;IBZBAS;UPSTOR;DUSTOR;
                                         1200.     1    0.    0.
                          INPUT # 22  (ABSTOR(1,L),L=1,NB);
                                           0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

: ............... GRAPHICAL OUTPUT CONTROL :
                          INPUT # 23  NGRAPH;PJSCAL;PHSCAL;GRAFBG;GRAFST;NNRAPH;PTSCAL;PPSCAL;PSTATS;
                                           1.  109.100000.   1.    7.   -1.   100.   250.   -1.

              [illegible] CONTROL :
                          INPUT # 24  NDAILS;NWKEUP;NWKUP2;NWKUPG;
                                          -1     0     0     0
```

TABLE B-4 - UBC WATERSHED MODEL CALIBRATION PARAMETERS -
UPPER ARROW LOCAL SUB-BASIN

```
: ............ HYDROLOGIC  ANALYSIS  PROGRAM  :
: .......  UBC  WATERSHED  MODEL  (DEC 1976)  :
: .......................... JOB  REFERENCE  :
                         INPUT  0  1   ..YEAR;PTHEAD;
                                       1969. LOWER ARROW LAKE 093  DJB       : FAU  ONLY  WED JAN 02/80 16.10
: ...................... EXECUTION  CONTROL  :
                         INPUT  0  2   NMONTH;MSTART;....NS;....NB;....MB;..ILAK;IAGLAC;IRABAT;ISNOBE;
                                         96    12     1    11    11     0     0     0     0
: ................ WATERSHED  REPRESENTATION  :
                         INPUT  0  3   (ELL(L),L=1,NB);
                                       1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                         INPUT  0  4   (A(L),L=1,NB);
                                       163.77 114.44 131.21 139.10 147.80 140.09  89.78  47.35  13.81   0.0    0.0
                         INPUT  0  5   ..ALAK;STAREA;
                                        0.0    0.0
: ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                         INPUT  0  6   (EL(I),I=1,NS);
                                       1400.
: .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                         INPUT  0  7   ELLXPL;ELLXPU;ELNORG;STABIF;TRFORM;LOUPSI;MSCHLT;MSLYBD;MSLYST;
                                        4000.  4000.  2000. 0.0070  35.0     0      0      1     12
                         INPUT  0  8   (SNORFP(I),I=1,NS);(RAINFP(I),I=1,NS);
                                        -0.70  -0.60
: .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                         INPUT  0  9   TZLAPS;MSLAPS;MSBASE;IVALYT;TBNREP;TBNLOC;
                                         3.3    -1     0      0    64.    64.
: ........ SNOWMELT  CALCULATION  PARAMETERS  :
                         INPUT  0 10   PTSMLT;XTBEMP;XTBSUN;XTCEMX;ANMLTF;IMLTFN;IWEDGE;.ZENCN;..ZALB;
                                         4.5    64.    2.    1.0   0.96    10     -1   0.0    0.0


                         INPUT  0 11   AETREN;DELAES;.PKIMP;DELPXP;AREGEN;
                                         600.    50.   0.01   0.0   400.
                         INPUT  0 12   SMPERC;DZSNPE;DELBZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISNBE;IABSTR;
                                         40.   0.99  0.99999999.     0   0.99     0   0.0      1
                         INPUT  0 13   (AGSMAX(L),L=1,NB);
                                        200.   200.   200.   300.   400.   400.   400.   400.   400.   400.   400.
                         INPUT  0 14   (AGSSTK(L),L=1,NB);
                                       0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500

: ........... WATERSHED  ROUTING  PARAMETERS  :
                         INPUT  0 15   ...NUM;NRESVO;UNHYDK;UTRFLD;IHTSTK;...LAG;
                                          10     2.    0.0    0.0   1.00     0
                         INPUT  0 16   UGWSTK;DZWSTK;LAGGAS;UPSSTK;SURSTK;
                                        0.040 0.0020     0  0.020  0.020
: ......... WATERSHED  STATE  INITIALIZATION  :
                         INPUT  0 17   (SNOPAK(L),L=1,NB);
                                          0.   300.   900.  1300.  1400.  1500.  1500.  1600.  1700.  1700.  1700.
                         INPUT  0 18   (SOILBF(L),L=1,NB);
                                          0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                         INPUT  0 19   (INTFLS(L),L=1,NB);
                                          0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                         INPUT  0 20   BASFLO;IBZBAS;UPSTOR;BUSTOR;
                                        300.     1     0.     0.
                         INPUT  0 21   (ABSTOR(1,L),L=1,NB);
                                          0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

: ............... GRAPHICAL  OUTPUT  CONTROL  :
                         INPUT  0 22   NGRAPH;PJBCAL;PNBCAL;GRAFBD;GRAFST;MGRAPH;PTSCAL;PPSCAL;PSTATS;
                                          1.   100. 25000.    1.    12.    -1.   100.   250.    -1.
: ................. PRINTED  OUTPUT  CONTROL  :
                         INPUT  0 23   NDAILS;MAKEUP;MAKUP2;MAKUP3;
                                          -1      0      0      0
```

TABLE B-5 - UBC WATERSHED MODEL CALIBRATION PARAMETERS - LOWER ARROW SUB-BASIN

```
  . ..... UBC WATERSHED MODEL [illegible] !
! ......................... JOB REFERENCE !
                       INPUT # 1   ..YEAR,PTHEAD!
                                   1966. ADDT B TOTAL TO STE  ! FEB ONLY  THU DEC 06  18.43

! ........................ EXECUTION CONTROL !
                       INPUT # 2   MMONTH,MSTART!....MB!....MB!....MB!..ILAK;IAGLAC;IRADAT;ISNODE!
                                   132    12     1    11    11     0     0     0     0

! ................ WATERSHED REPRESENTATION !
                       INPUT # 3   (ELL(L),L=1,MB)!
                                   1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                       INPUT # 4   (A(L),L=1,MB)!
                                   0.0  244.40 410.60 437.00 507.00 664.50 717.50 790.00 426.00 166.70  34.30
                       INPUT # 5   ..ALAK;STAREA!
                                   0.0   0.0

! ...... METEOROLOGICAL  STATION  ELEVATIONS !
                       INPUT # 6   (EL(I),I=1,MS)!
                                   1930.

! .. PRECIPITATION  DISTRIBUTION  PARAMETERS !
                       INPUT # 7   ELLXPL;ELLXPU;ELHOPO;STABIF;TRFORM;LOUPSI;NSOHLT;NSLTGO;NSLTST!
                                   5250.  5250.  4500. 0.0050  35.0     0     0     1    12
                       INPUT # 8   (SNOREP(I),I=1,MS);(RAINREP(I),I=1,MS)!
                                   -0.04  -0.03

! .... TEMPERATURE  DISTRIBUTION  PARAMETERS !
                       INPUT # 9   TZLAPS;NSLAPS;NSBASE;IVALYT;TRHREP;TRHLOC!
                                   3.0    -1     0     0   64.   64.

! ........ SNOWMELT  CALCULATION  PARAMETERS !
                       INPUT # 10  PTSMLT;XTDEMP;XTDIUM;XTCEMX;ANMLTF;IMLTFN;INEDGE!.ZENCH!..ZALB!
                                   4.5   60.    2.   1.0  0.96    10    -1   0.0   0.0

! .......... RUNOFF  CALCULATION  PARAMETERS !
                       INPUT # 11  AETGEM;DELAEB!.MXIMP;DELMXP;AREGEN!
                                   150.   150.   0.60   0.0.   400.
                       INPUT # 12  SWPERC;DZSHRE;DELDZS;UPSMAX!..IUPS;UPSPCR;IREUPS;RISHRE;IABSTR!
                                   16.   0.60   0.40999999.     0  0.50      0  0.0       1
                       INPUT # 13  (ABSMAX(L),L=1,MB)!
                                   200.   200.   200.   300.   300.   300.   400.   400.   400.   400.   400.
                       INPUT # 14  (ABSSTK(L),L=1,MB)!
                                   0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0300 0.0300 0.0300

! ........... WATERSHED  ROUTING  PARAMETERS !
                       INPUT # 15  ...NUH;NRESVO;UHNTBK;UTRFLO;INTSTK!...LAG!
                                   10     2.    0.0    0.0   1.00      2
                       INPUT # 16  UGWSTK;DZNSTK;LAGBAS;UPSSTK;SURSTK!
                                   0.030 0.0020      0 0.030 0.030

! ......... WATERSHED  STATE  INITIALIZATION !
                       INPUT # 17  (SNOPAK(L),L=1,MB)!
                                   0.     0.   575.   763.  1150.  1750.  2400.  2400.  2400.  2400.  2400.
                       INPUT # 18  (SOILDF(L),L=1,MB)!
                                   0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                       INPUT # 19  (INTFLS(L),L=1,MB)!
                                   0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                       INPUT # 20  BASFLO;IDZBAS;UPSTOR;SURSTOR!
                                   1230.     1    0.    0.
                       INPUT # 21  (ABSTOR(1,L),L=1,MB)!
                                   0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

! ............... GRAPHICAL  OUTPUT  CONTROL !
                       INPUT # 22  NGRAPH;PJSCAL;PHSCAL;GRAFGO;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS!
                                   1.   100. 50000.    1.     7.    -1.   100.   250.    -1.

! ................. PRINTER  OUTPUT  CONTROL !
                       INPUT # 23  NDAILY;MAFLWP;MAXUPZ;MAFUPG!
                                   -1      0      0      0
```

TABLE B-6 - UBC WATERSHED MODEL CALIBRATION
PARAMETERS - FT. STEELE SUB-BASIN

```
: ............. HYDROLOGIC  ANALYSIS  PROGRAM  :
: .......  UBC  WATERSHED  MODEL  (DEC 1976)  :
: ........................... JOB  REFERENCE  :
                            INPUT  # 1   ..YEAR;PTHEAD;
                                          1966. LIBBY RESR R89  OJB  :  CRA & KAS/THU DEC 13 21.11
: ...................... EXECUTION  CONTROL  :
                            INPUT  # 2   NMONTH;MSTART;....NS;....NB;....ND;..ILAK;IAGLAC;IRADAT;ISNODE;
                                           132    12     2    11    31     0     0     0     0
: ................ WATERSHED  REPRESENTATION  :
                            INPUT  # 3   (ELL(L),L=1,NB);
                                          1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                            INPUT  # 4   (A(L),L=1,NB);
                                          130.00 433.00 467.00 655.00 660.00 780.10 654.90 370.00 180.00  65.60  10.00
                            INPUT  # 5   ..ALAK;STAREA;
                                           0.0    0.0
: ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                            INPUT  # 6   (EL(I),I=1,NS);
                                          1845.  1930.
: .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                            INPUT  # 7   ELLKPL;ELLKPU;ELNORO;STABIF;TRFORM;LOUPSI;NSONLY;NBLYGO;NBLYST;
                                          4000. 14000.  4500. 0.0100   35.0     2     0     1    12
                            INPUT  # 8   (SNOREP(I),I=1,NS);(RANREP(I),I=1,NS);
                                          -0.75  -0.80  -0.50  -0.75
: .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                            INPUT  # 9   TZLAPS;NSLAPS;NSBASE;IVALYT;TRNREP;TRNLOC;
                                           3.0    -1     0     2   64.    64.
: ........ SNOWMELT  CALCULATION  PARAMETERS  :
                            INPUT  # 10  PTSMLT;XTDEMP;XTDIUN;XTCEMX;ANMLTF;IMLTFN;INEDGE;.ZEXCH;..ZALB;
                                           4.5    60.     2.    1.0   0.90    10    -1   0.0    0.0
: .......... RUNOFF  CALCULATION  PARAMETERS  :
                            INPUT  # 11  AETGEN;DELAEG;.MXIMP;DELMXP;AREGEN;
                                           400.    50.   0.01   0.0    400.
                            INPUT  # 12  GWPERC;DZSHRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISHRE;IABSTR;
                                           40.   0.90   0.99999999.    11   0.99     0   0.0      1
                            INPUT  # 13  (ABSMAX(L),L=1,NB);
                                           200.   200.   300.   300.   300.   300.   400.   400.   400.   400.   400.
                            INPUT  # 14  (ABSSTK(L),L=1,NB);
                                          0.2500 0.2500 0.2500 0.2500 0.1000 0.1000 0.0300 0.0300 0.0300 0.0300 0.0300
: ........... WATERSHED  ROUTING  PARAMETERS  :
                            INPUT  # 15  ...NUN;NRESVO;UNNYDK;UTRFLO;INTSTK;...LAG;
                                            10     2.    1.0    0.0   1.00      0
                            INPUT  # 16  UGWSTK;BZWSTK;LAGBAS;UPSSTK;SURSTK;
                                          0.030 0.0020      0  0.030  0.030
: ......... WATERSHED  STATE  INITIALIZATION  :
                            INPUT  # 17  (SNOPAK(L),L=1,NB);
                                            0.     0.  1300.  1700.  2000.  2400.  2800.  2800.  2800.  2800.  2800.
                            INPUT  # 18  (SOILDF(L),L=1,NB);
                                            0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                            INPUT  # 19  (INTFLS(L),L=1,NB);
                                            0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                            INPUT  # 20  BASFLO;IBZBAS;UPSTOR;SUSTOR;
                                          1900.     1     0.     0.
                            INPUT  # 21  (ABSTOR(1,L),L=1,NB);
                                            0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
: ................ GRAPHICAL  OUTPUT  CONTROL  :
                            INPUT  # 22  NGRAPH;PJSCAL;PNSCAL;GRAFGO;GRAFST;MGRAPH;PTSCAL;PPSCAL;PSTATS;
                                           1.   100. 50000.    1.    12.    -1.   100.   250.    -1.
: ................. PRINTED  OUTPUT  CONTROL  :
                            INPUT  # 23  [illegible]
                                           -1      0      0      0
```

TABLE B-7 - UBC WATERSHED MODEL CALIBRATION PARAMETERS - LIBBY LOCAL SUB-BASIN

```
: ............. HYDROLOGIC ANALYSIS PROGRAM :
: ....... UBC WATERSHED MODEL (DEC 1976) :
: ............................ JOB REFERENCE :
                              INPUT # 1   ..YEAR;PTHEAD;
                                           1968. LOCAL PORTHILL RSB REPEAT TESTOR! CRE + KAB  WED JAN 02/80 15.44
: ........................ EXECUTION CONTROL :
                              INPUT # 2   NMONTH;NSTART;....NS;....NB;....ND;..ILAK;IAGLAC;IRABAT;ISNODE;
                                            106    12     2    11    11     0     0     0     0
: ................. WATERSHED REPRESENTATION :
                              INPUT # 3   (ELL(L),L=1,NB);
                                           1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                              INPUT # 4   (A(L),L=1,NB);
                                           220.00 459.00 771.00 990.001060.00 531.00 208.00  42.72   0.0    0.0    0.0
                              INPUT # 5   ..ALAK;STAREA;
                                            0.0    0.0
: ...... METEOROLOGICAL STATION ELEVATIONS :
                              INPUT # 6   (EL(I),I=1,NS);
                                           2085.  1930.
: .. PRECIPITATION DISTRIBUTION PARAMETERS :
                              INPUT # 7   ELLKPL;ELLKPU;ELNORO;STADIF;TRFORM;LOUPSI;NSONLY;NSLYBD;NSLYST;
                                            3400.  3400.  3400. 0.0058   32.1     9     0     1    12
                              INPUT # 8   (SNOREP(I),I=1,NS);(RAHREP(I),I=1,NS);
                                            -0.70  -0.70  -0.65  -0.65
: .... TEMPERATURE DISTRIBUTION PARAMETERS :
                              INPUT # 9   TZLAPS;NSLAPS;NSBASE;IVALYT;TRNREP;TRNLOC;
                                             3.0     -1      0      2    64.    64.
: ........ SNOWMELT CALCULATION PARAMETERS :
                              INPUT # 10  PTSMLT;XTDEMP;XTDIUN;XTCEMX;ANMLTF;INLTFN;INEDGE;.ZEXCH;..ZALB;
                                             4.5    60.     2.    1.0   0.90     10    -1   0.0    0.0
: .......... RUNOFF CALCULATION PARAMETERS :
                              INPUT # 11  AETGEN;DELAEG;.MXIMP;DELMXP;AREGEN;
                                            1000.   100.   0.01   0.0    400.
                              INPUT # 12  GWPERC;DZSNRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISNRE;IABSTR;
                                             24.   0.99   0.50999999.      7   0.99      0   0.0       1
                              INPUT # 13  (ABSMAX(L),L=1,NB);
                                            900.   900.   900.   900.   900.   900.   900.  1200.  1200.  1200.  1200.
                              INPUT # 14  (ABSSTK(L),L=1,NB);
                                           0.1000 0.1000 0.1000 0.1000 0.1000 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600

: ........... WATERSHED ROUTING PARAMETERS :
                              INPUT # 15  ...NUH;NRESVD;UNHYDK;UTRFLO;INTSTK;...LAG;
                                             10     2.    1.0    0.0   1.00      0
                              INPUT # 16  UGWSTK;DZNSTK;LAGBAS;UPSSTK;SURSTK;
                                            0.030 0.0020      0  1.000  1.000
: ......... WATERSHED STATE INITIALIZATION :
                              INPUT # 17  (SNOPAK(L),L=1,NB);
                                             156.   355.   654.  1200.  2212.  2545.  2757.  2821.  2894.  2894.  2894.
                              INPUT # 18  (SOILDF(L),L=1,NB);
                                              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT # 19  (INTFLS(L),L=1,NB);
                                              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT # 20  BASFLO;IDZBAS;UPSTOR;SUSTOR;
                                            2000.     1     0.     0.
                              INPUT # 21  (ABSTOR(1,L),L=1,NB);
                                              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

: ................ GRAPHICAL OUTPUT CONTROL :
                              INPUT # 22  NGRAPH;PJSCAL;PHSCAL;GRAFBD;GRAFST;MGRAPH;PTSCAL;PPSCAL;PSTATS;
                                              1.   100. 25000.    1.    12.    -1.   100.   250.    -1.
: .................. PRINTED OUTPUT CONTROL :
                              INPUT # 23  NDAILS;MAKEUP;MAKUP2;MAKUPG;
                                              -1      0      0      0
```

TABLE B-8 - UBC WATERSHED MODEL CALIBRATION PARAMETERS -
PORTHILL LOCAL SUB-BASIN

```
: ............ [illegible] ANALYSIS  PROGRAM  :
 : .......  UBC  WATERSHED  MODEL  (DEC 1976)  :
 : .......................... JOB  REFERENCE  .
                              INPUT  # 1   ..YEAR;PTHEAD;
                                            1967. DUNCAN LAKE ..AVE RVA+LAR  AND  GRP THU DEC 20 1979 10.00
 : ....................... EXECUTION  CONTROL  :
                              INPUT  # 2   NMONTH;MSTART;....MS;....MB;....MD;..ILAK;IAGLAC;IRADAT;ISNODE;
                                             120    12     2    11    31     0     1     0     0
 : ................ WATERSHED  REPRESENTATION  :
                              INPUT  # 3   (ELL(L),L=1,MB);
                                            1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                              INPUT  # 4   (A(L),L=1,MB);
                                            45.00  36.00  53.00  84.00 103.00 124.00 140.00 146.00 120.00  57.00  26.00
                              INPUT  # 5   (AG(L),L=1,MB);
                                             0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   30.00  50.00  20.00
                              INPUT  # 6   ..ALAK;STAREA;
                                             0.0    0.0
 : ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                              INPUT  # 7   (EL(I),I=1,MS);
                                            1636.  4340.
 .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 8   ELLXPL;ELLXPU;ELHORD;STABIF;TRFORM;LOUPSI;HSONLY;HSLYGO;HSLYST;
                                            30000. 30000.  2500. 0.0055   35.0     1      0      1     12
                              INPUT  # 9   (SNOREP(I),I=1,MS);(RANREP(I),I=1,MS);
                                             0.0    0.0    0.0    0.20
 : .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 10   TZLAPS;MSLAPS;MSBASE;IVALYT;TRMREP;TRMLOC;
                                             3.3    -1     0     1   64.    64.
 : ........ SNOWMELT  CALCULATION  PARAMETERS  :
                              INPUT  # 11   PTSMLT;XTDEWP;XTDIUN;XTCEMX;AHMLTF;IMLTFN;IWEDGE;.ZEXCH;..ZALB;
                                             4.5   60.    2.    1.0   0.96    11     -1   0.0    0.0

 : .......... RUNOFF  CALCULATION  PARAMETERS  :
                              INPUT  # 12   AETGEN;DELAES;.MXIMP;DELUXP;AREGEN;
                                             500.   100.   0.05   0.0    400.
                              INPUT  # 13   GWPERC;DZSHRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISHRE;IABSTR;
                                             10.   0.75  0.75999999.     0   0.10      0   0.0      1
                              INPUT  # 14   (ABSMAX(L),L=1,MB);
                                             200.   200.   200.   200.   300.   500.   800.  1000.  1000.  1400.  1600.
                              INPUT  # 15   (ABSSTK(L),L=1,MB);
                                            0.3000 0.3000 0.3000 0.3000 0.3000 0.2500 0.2000 0.1000 0.1000 0.1000 0.1000

 : ........... WATERSHED  ROUTING  PARAMETERS  :
                              INPUT  # 16   ...NUN;NRESVO;UNHYDK;UTRFLO;INTSTK;...LAG;
                                              10     2.    1.0    0.0   1.00      1
                              INPUT  # 17   UGWSTK;DZHSTK;LAGBAS;UPSSTK;SURSTK;
                                             0.040 0.0020     0  0.100  0.100
 : ......... WATERSHED  STATE  INITIALIZATION  :
                              INPUT  # 18   (SNOPAK(L),L=1,MB);
                                             400.  1900.  2600.  3200.  3600.  4000.  4000.  4000.  4000.  4000.  4000.
                              INPUT  # 19   (SOILDF(L),L=1,MB);
                                              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 20   (INTFLS(L),L=1,MB);
                                              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 21   BASFLO;IDZBAS;UPSTOR;SUSTOR;
                                              80.    1     0.     0.
                              INPUT  # 22   (ABSTOR(1,L),L=1,MB);
                                              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

 : ................ GRAPHICAL  OUTPUT  CONTROL  :
                              INPUT  # 23   NGRAPH;PJSCAL;PHSCAL;GRAFGO;GRAFST;MGRAPH;PTSCAL;PPSCAL;PSTATS;
                                              1.   100. 25000.    1.     7.    -1.   100.   250.    -1.
 : ..........  PRINTED  OUTPUT  CONTROL  :
                              INPUT  # 24   NDAILS;MAKEUP;MAKUP2;MAKUPG;
                                              -1     0     0     0
```

TABLE B-9 - UBC WATERSHED MODEL CALIBRATION
PARAMETERS - DUNCAN SUB-BASIN

```
 : ............ HYDROLOGIC  ANALYSIS  PROGRAM  :
 : ....... UBC  WATERSHED  MODEL  (DEC 1976)  :
 : ........................... JOB  REFERENCE  :
                              INPUT  # 1   ..YEAR;PTHEAD;
                                            1967. WEST KOOT LAKE @ CORRA LINN     : HEL + KAS  WED DEC 19/79 10.55
 : ....................... EXECUTION  CONTROL  :
                              INPUT  # 2   NMONTH;MSTART;....NS;....NB;....ND;..ILAK;IAGLAC;IRADAT;ISNODE;
                                             120     12      2     11     11      0      0      0      0
 : ............... WATERSHED  REPRESENTATION  :
                              INPUT  # 3   (ELL(L),L=1,NB);
                                             1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                              INPUT  # 4   (A(L),L=1,NB);
                                            373.57 225.43 281.04 377.16 502.00 622.92 634.20 341.24 161.64  61.84  10.00
                              INPUT  # 5   ..ALAK;STAREA;
                                             0.0    0.0
 : ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                              INPUT  # 6   (EL(I),I=1,NS);
                                             1980.  1930.
 : .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 7   ELLKPL;ELLKPU;ELNORD;STABIF;TRFORM;LOUPSI;NSONLY;NSLYBD;NSLYST;
                                            14000. 30000.  3750. 0.0055   35.0      1      0      1     12
                              INPUT  # 8   (SNOREP(I),I=1,NS);(RANREP(I),I=1,NS);
                                             0.0    0.0    0.10   0.15
 : .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                              INPUT  # 9   TZLAPS;NSLAPS;NSBASE;IVALYT;TRNREP;TRNLOC;
                                              3.3     -1      0      2    64.    64.
 : ........ SNOWMELT  CALCULATION  PARAMETERS  :
                              INPUT  # 10  PTSMLT;XTDEMP;XTDIUN;XTCEMX;ANMLTF;IMLTFN;INEDGE;.ZEXCH;..ZALB;
                                              4.5    60.     2.    1.0   0.95     10     -1    0.0    0.0
 . .......... RUNOFF  CALCULATION  PARAMETERS  :
                              INPUT  # 11  AETGEN;DELAEG;.MXIMP;DELMXP;AREGEN;
                                              600.    50.   0.01    0.0    400.
                              INPUT  # 12  GWPERC;DZSHRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISHRE;IABSTR;
                                               20.   0.25  0.20999999.     11   0.99      0    0.0      1
                              INPUT  # 13  (ABSMAX(L),L=1,NB);
                                              300.   300.   300.   300.   300.   300.   300.  1000.  1000.  1000.  1000.
                              INPUT  # 14  (ABSSTK(L),L=1,NB);
                                            0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.1000 0.0300 0.0300 0.0300 0.0300
 : ........... WATERSHED  ROUTING  PARAMETERS  :
                              INPUT  # 15  ...NUH;NRESVO;UNHYDK;UTRFLO;INTSTK;...LAG;
                                               10     2.    1.0    0.0   1.00      0
                              INPUT  # 16  UGWSTK;DZHSTK;LAGBAS;UPSSTK;SURSTK;
                                             0.030 0.0020      0  0.100  0.100
 : ......... WATERSHED  STATE  INITIALIZATION  :
                              INPUT  # 17  (SNOPAK(L),L=1,NB);
                                               0.   272.  1369.  1872.  2177.  2444.  2450.  2600.  2600.  2600.  2600.
                              INPUT  # 18  (SOILDF(L),L=1,NB);
                                               0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 19  (INTFLS(L),L=1,NB);
                                               0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                              INPUT  # 20  BASFLO;IBZBAS;UPSTOR;SUSTOR;
                                             4231.     1     0.     0.
                              INPUT  # 21  (ABSTOR(1,L),L=1,NB);
                                               0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
 : ............... GRAPHICAL  OUTPUT  CONTROL  :
                              INPUT  # 22  NGRAPH;PJSCAL;PHSCAL;GRAFGO;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS;
                                               1.  100.100000.    1.    12.    -1.   100.   250.    -1.
 : ................. PRINTED  OUTPUT  CONTROL  :
                              INPUT  # 23  NDAILS;MAKEUP;MAKUP2;MAKUPG;
                                              -1      0      0      0
```

TABLE B-10 - UBC WATERSHED MODEL CALIBRATION PARAMETERS - KOOTENAY LAKE SUB-BASIN

```
/ : ............ HYDROLOGIC  ANALYSIS  PROGRAM  :
  . ...... UBC  WATERSHED  MODEL  (DEC 1976)  :
  : ........................... JOB  REFERENCE  :
                            INPUT  # 1   ..YEAR;PTHEAD;
                                          1966. SLOCAN RIVER AT CRESCENT VALLEY : FAU + KAB  WED DEC 19/79 10.41
  : ...................... EXECUTION  CONTROL  :
                            INPUT  # 2   NMONTH;MSTART;....NS;....NB;....ND;..ILAK;IAGLAC;IRABAT;ISNODE;
                                           132    12     2    11    31     0     0     0     0
  : ............... WATERSHED  REPRESENTATION  :
                            INPUT  # 3   (ELL(L),L=1,NB);
                                          1875.  2625.  3375.  4125.  4875.  5625.  6375.  7125.  7875.  8625.  9375.
                            INPUT  # 4   (A(L),L=1,NB);
                                          98.80  91.40 116.60 140.80 179.80 237.70 232.30 136.00  53.60   9.70   0.0
                            INPUT  # 5   ..ALAK;STAREA;
                                           0.0   0.0
  : ...... METEOROLOGICAL  STATION  ELEVATIONS  :
                            INPUT  # 6   (EL(I),I=1,NS);
                                          1400.  1930.
  . .. PRECIPITATION  DISTRIBUTION  PARAMETERS  :
                            INPUT  # 7   ELLXPL;ELLXPU;ELNORD;STABIF;TRFORM;LOUPSI;NSOHLY;NSLYSD;NSLYST;
                                          7000. 30000.  3000. 0.0055  35.0     3     0     1    12
                            INPUT  # 8   (SNOREP(I),I=1,NS);(RAINREP(I),I=1,NS);
                                          -0.20  -0.10   0.0    0.0
  : .... TEMPERATURE  DISTRIBUTION  PARAMETERS  :
                            INPUT  # 9   TZLAPS;NSLAPS;NSBASE;IVALYT;TMNREP;TMNLOC;
                                           3.3    -1     0     2   64.   64.
  : ........ SNOWMELT  CALCULATION  PARAMETERS  :
                            INPUT  # 10  PTSMLT;XTDEMP;XTDIUM;XTCEMX;ANMLTF;IMLTFN;INEDGE;.ZENCH;..ZALB;
                                           4.5   56.    2.   1.0  0.96    10    -1   0.0   0.0

  ........... RUNOFF  CALCULATION  PARAMETERS  :
                            INPUT  # 11  AETGEN;DELAEG;.MXIMP;DELMXP;AREGEN;
                                           500.   50.  0.01   0.0   400.
                            INPUT  # 12  GWPERC;DZSHRE;DELDZS;UPGMAX;..IUPS;UPSPCR;IREUPS;RISHRE;IABSTR;
                                           24.  0.90  0.75999999.     0  0.80     0   0.0     1
                            INPUT  # 13  (ABSMAX(L),L=1,NB);
                                           300.   300.   300.   300.   300.   300.  1200.  1200.  1500.  1500.  1500.
                            INPUT  # 14  (ABSSTK(L),L=1,NB);
                                          0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600 0.0600

  : ........... WATERSHED  ROUTING  PARAMETERS  :
                            INPUT  # 15  ...NUM;NRESVD;UGNYDK;UTRFLO;INTSTK;...LAG;
                                            10     2.    1.0    0.0   1.00     0
                            INPUT  # 16  UGMSTK;DZNSTK;LAGBAS;UPSSTK;SURSTK;
                                           0.040 0.0020     0  0.010  0.010
  : ......... WATERSHED  STATE  INITIALIZATION  :
                            INPUT  # 17  (SNOPAK(L),L=1,NB);
                                           400.   800.  1600.  3800.  3800.  3800.  3700.  3700.  3700.  3700.  3700.
                            INPUT  # 18  (SOILDF(L),L=1,NB);
                                            0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                            INPUT  # 19  (INTFLS(L),L=1,NB);
                                            0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
                            INPUT  # 20  BASFLO;IBZBAS;UPSTOR;BUSTOR;
                                           620.     1    0.    0.
                            INPUT  # 21  (ABSTOR(1,L),L=1,NB);
                                            0.     0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

  : ............... GRAPHICAL  OUTPUT  CONTROL  :
                            INPUT  # 22  NGRAPH;PJSCAL;PNSCAL;GRAFGO;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS;
                                           100.   100. 25000.    1.   12.   -1.   100.   200.   -1.
  : ................. PRINTED  OUTPUT  CONTROL  :
                            INPUT  # 23  ...LS;NVTUP;NAVUP2;NAVUPG;
                                            -1     0     0     0
```

TABLE B-11 - UBC WATERSHED MODEL CALIBRATION
PARAMETERS - SLOCAN SUB-BASIN

```
: ............. HYDROLOGIC ANALYSIS PROGRAM :
: ....... UBC WATERSHED MODEL (DEC 1976) :
: ........................... JOB REFERENCE :
                        INPUT # 1   ..YEAR;PTHEAD;
                                    1969. BIRC LOCAL CF LAPO          : FAU ONLY WED JAN 02/80 14.17
: ...................... EXECUTION CONTROL :
                        INPUT # 2   NMONTH;MSTART;....ND;....ND;....ND;..ILAK;IADLAC;IRABAT;ISNODE;
                                      96    12     1    11    11     0     0     0     0
: ................ WATERSHED REPRESENTATION :
                        INPUT # 3   (ELL(L),L=1,NB);
                                    1875. 2625. 3375. 4125. 4875. 5625. 6375. 7125. 7875. 8625. 9375.
                        INPUT # 4   (A(L),L=1,NB);
                                    70.00 45.00 50.00 72.00 77.00 54.00 30.00 12.00  0.0   0.0   0.0
                        INPUT # 5   ..ALAK;STAREA;
                                     0.0   0.0
: ...... METEOROLOGICAL STATION ELEVATIONS :
                        INPUT # 6   (EL(I),I=1,NS);
                                    1400.
: .. PRECIPITATION DISTRIBUTION PARAMETERS :
                        INPUT # 7   ELLKPL;ELLKPU;ELHORO;STABIF;TRFORM;LOUPSI;NSONLY;NS.TSO;NSLYST;
                                    4000. 4000. 2000. 0.0070  35.0    0     0     1    12
                        INPUT # 8   (SNOREP(I),I=1,NS);(RANREP(I),I=1,NS);
                                    -0.70 -0.40
: .... TEMPERATURE DISTRIBUTION PARAMETERS :
                        INPUT # 9   TZLAPS;NSLAPS;NSBASE;IVALTT;TRNREP;TRNLOC;
                                      3.5   -1     0     0   64.   64.
: ........ SNOWMELT CALCULATION PARAMETERS :
                        INPUT # 10  PTSMLT;XTDEMP;XTDIUN;XTCEMX;AMMLTF;IMLTFN;IWEDGE;.ZENCH;..ZALB;
                                      4.5   60.    2.   1.0  0.96    10    -1  0.0   0.0
: .......... RUNOFF CALCULATION PARAMETERS :
                        INPUT # 11  AETGEN;DELAEB;.MXIMP;DELMXP;ARESEN;
                                     600.   50.  0.01   0.0   400.
                        INPUT # 12  GMPERC;DZSNRE;DELDZS;UPSMAX;..IUPS;UPSPCR;IREUPS;RISNRE;IADSTR;
                                      40.  0.99  0.99997999.     0  0.99     0  0.0      1
                        INPUT # 13  (ABSMAX(L),L=1,NB);
                                     200.  200.  200.  300.  400.  400.  400.  400.  400.  400.  400.
                        INPUT # 14  (ABSSTK(L),L=1,NB);
                                    0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500 0.2500
: ........... WATERSHED ROUTING PARAMETERS :
                        INPUT # 15  ...NUN;NRESVO;UNHYDK;UTRFLO;INTSTK;...LAG;
                                       10    2.   0.0   0.0  1.00     0
                        INPUT # 16  UGWSTK;DZWSTK;LAGBAS;UPSSTK;SURSTK;
                                    0.040 0.0020     0  0.020  0.020
: ......... WATERSHED STATE INITIALIZATION :
                        INPUT # 17  (SNOPAK(L),L=1,NB);
                                       0.   300.  900. 1300. 1400. 1500. 1550. 1600. 1700. 1700. 1700.
                        INPUT # 18  (SOILBF(L),L=1,NB);
                                       0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
                        INPUT # 19  (INTPLS(L),L=1,NB);
                                       0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
                        INPUT # 20  BASFLO;IBZBAS;UPSTOR;SUSTOR;
                                      80.    1    0.    0.
                        INPUT # 21  (ABSTOR(1,L),L=1,NB);
                                       0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
: ................ GRAPHICAL OUTPUT CONTROL :
                        INPUT # 22  NGRAPH;PJSCAL;PHSCAL;GRAFBG;GRAFST;NGRAPH;PTSCAL;PPSCAL;PSTATS;
                                       1.   100. 25000.    1.   12.   -1.  100.  250.   -1.
: ................. PRINTED OUTPUT CONTROL :
                        INPUT # 23  IDAILS;MAKEUP;MAKUP2;MAKUPG;
                                       -1     0     0     0
```

TABLE B-12 - UBC WATERSHED MODEL CALIBRATION PARAMETERS -
BIRCHBANK LOCAL SUB-BASIN

APPENDIX C

REGULATION OF EXTREME FLOODS

APPENDIX C

REGULATION OF EXTREME FLOODS

CONTENTS

Section	Subject	Page
C.1	INTRODUCTION	C - 1
C.2	FLOOD CONDITIONS UPSTREAM OF THE MURPHY CREEK PROJECT	C - 3
C.3	FLOOD CONDITIONS DOWNSTREAM OF THE MURPHY CREEK PROJECT	C - 6
C.4	SUMMARY	C - 6

FIGURES

Figure No.	
C-1	Hydrographs at Murphy Creek Project - 72AP16MY16 Sequence
C-2	Hydrographs at Murphy Creek Project - 72MY16JN15 Sequence
C-3	Hydrographs at Murphy Creek Project - 76MY01JL27 Sequence
C-4	Hydrographs at Murphy Creek Project - 76MY16JL27 Sequence
C-5	Hydrographs at Murphy Creek Project - 76JN01JL27 Sequence
C-6	Hydrographs at Murphy Creek Project - 76JN16JL16 Sequence
C-7	Hydrographs at Murphy Creek Project - 76JN16JL27 Sequence
C-8	Hydrographs at Murphy Creek Project - 76JN27JL27 Sequence
C-9	Peak Discharges of Estimated Probable Maximum Floods for Damsites within the Columbia River Basin

APPENDIX C
REGULATION OF EXTREME FLOODS

C.1 INTRODUCTION

The conditions that would produce the highest regulated flows at the Murphy Creek project were identified in an analysis of extreme flood events and the 1972 Columbia River Flood Control Operating Plan. The purpose of this appendix is to provide a summary of the extreme flood conditions that would be experienced at other upstream river control and project locations in the Columbia River basin.

The impact of the Columbia River Treaty project operations (at Mica, Arrow, Duncan and Libby) during extreme flood events was examined in Section 4.6 of the main report. Extreme flood events were developed from different combinations of severe winter snowpacks, severe summer temperature sequences and the Probable Maximum Rain event, and each of the extreme floods was regulated according to the 1972 Columbia River Flood Control Operating Plan. Two of the extreme floods were identified in Sections 4.5 and 4.6 of the main report as the Probable Maximum Unregulated Flood (PMUF) and the Probable Maximum Regulated Flood (PMRF). These floods produced the highest flows for the Columbia River at Trail under pre-treaty conditions (PMUF) and the highest regulated flows at the Murphy Creek project site under present day levels of upstream development (PMRF).

The highest regulated upstream flood levels along the main stem of the Columbia River were produced by the PMRF event. However, the highest regulated flood levels in the Kootenay River basin were produced by other extreme flood events that peaked earlier in the summer than the PMRF event. The extreme flood hydrographs at the Murphy Creek project site for the PMUF and the PMRF are shown in Figs. 4-2 and 4-3 of the main report. Figs. C-1 to C-8 in this appendix show the flood hydrographs at the Murphy Creek project site for other extreme flood events. These figures show that the upstream reservoir operations can effectively reduce the May and June levels of regulated flow at the Murphy Creek project site to below those that could occur at the end of July when all of the upstream reservoirs are full.

Several upstream flood control criteria were recognized by the procedures used for the regulation of extreme floods. These criteria determine the effectiveness of the upstream Columbia Treaty projects in reducing the extreme flood events to non-damaging levels throughout the Columbia River basin in Canada and are as follows:

1. Reservoir surcharge in upstream reservoirs above normal full pool levels would not be permitted, except where inevitable reservoir surcharge took place.

2. Streamflows at Revelstoke should be regulated to below 5660 m^3/s, if possible, when Arrow Reservoir reaches its full operating level, El. 440.7.

3. Major damage would occur along the shore of Kootenay Lake when its level reached El. 536.1.

4. Major damage would occur at Trail when flow levels reached 7930 m^3/s, and, if possible, flows should not exceed 6370 m^3/s.

Each one of these four conditions was violated or exceeded during the regulation of at least one of the extreme flood events.

C.2 FLOOD CONDITIONS UPSTREAM OF THE MURPHY CREEK PROJECT

(a) Flood Conditions at the Mica Project

The Mica Reservoir was drawn down to El. 722.7 in anticipation of the extreme flood events. Because of the large flood control storage space at the Mica project, the final stages of the refill operation could be scheduled for the latter half of July and filling could be timed for completion by 31 July.

The highest peak inflows to the project of 6170 m³/s occurred in early June with reservoir levels 15 m below the normal full supply level, El. 754.4. The need to pass outflows greater than 2300 m³/s only arose at the end of July as the full supply level was reached. The highest project outflow of 4530 m³/s was required to prevent surcharging of the reservoir and this condition occurred during the PMRF event.

(b) Flood Conditions at Revelstoke

The flood inflows to the Revelstoke project will be the result of a regulated runoff component from the area upstream of the Mica project and a natural runoff component from the local area between Mica dam and Revelstoke dam. When the Revelstoke project is completed, the reservoir will be held at the normal full supply elevation, El. 573.0. For the extreme flood events considered in this report, the outflow hydrograph was assumed to be the same as the inflow hydrograph.

The regulation at Mica dam allowed peak flows at Revelstoke to be controlled to a maximum discharge of 2970 m³/s in May and June. The highest flow at Revelstoke of 6430 m³/s resulted from the Probable Maximum Rain (PMR) event, at a time when the Mica and

Arrow reservoirs were full. With these extreme conditions, backwater effects along the Columbia River at the north end of Arrow Reservoir would cause local damage in the Revelstoke area.

(c) Flood Conditions at the Arrow Project

Inflows to the Arrow project are the result of the flow component at Revelstoke and a natural runoff component from the Arrow Lakes Reservoir drainage area. The highest peak inflow of 9060 m^3/s at the end of July occurred because the Mica Reservoir was full and because the flow component originating upstream of the Mica project could not be regulated. In May and June, the peak inflows were lower (7360 m^3/s) because the Mica Reservoir was not full and because the flow component upstream of the Mica project would be regulated.

During the refill period, the Arrow project releases were scheduled to meet the flood control objective for the Columbia River flows at Trail. For the extreme flood events, damaging flow levels at Trail could not be avoided and peak outflows from the Arrow project inevitably contributed directly to the peak of the PMRF for the Murphy Creek project. The maximum Arrow project outflow of 9030 m^3/s at El. 440.7, was passed for 2 days. Peak outflows from other extreme flood events peaking in May and June (3960 m^3/s to 4530 m^3/s) occurred several days after the peak inflow when the reservoir reached the full supply level, El. 440.7. This level was reached as early as 15 June and as late as 31 July.

(d) Flood Conditions at the Libby Project

The highest peak inflow to the Libby project coincided with the peak of the probable maximum snowmelt flood at the end of May. The peak discharge of 5950 m^3/s did not result from the PMR event which was centred over the Arrow Lakes watershed. Peak outflows of between 2830 m³/s and 3400 m³/s occurred with the filling of the reservoir in early June; other extreme flood events required maximum releases in late June and July of 1700 m³/s. Outflows were maintained at less than 850 m³/s during the early refill period to avoid damaging flow levels downstream of the Libby project in Montana and Idaho. This procedure did not prevent the occurrence of these damaging flood levels later in May and June during the regulation of the PMUF and other extreme flood events.

(e) Flood Conditions of the Duncan Project

Peak inflows to the Duncan project of between 990 m³/s and 1360 m³/s occurred during each of the extreme flood events. The highest inflows in May and the first half of June occurred with reservoir levels below the normal full supply level, El. 576.7. Operation of the spillway may cause damage in the downstream area and it was conservatively assumed here that the spillway would not be operated during an extreme flood. Sufficient outflow capacity was available through the gated tunnels to pass the late summer inflows without excessive reservoir surcharge. The 820 m³/s capacity of the tunnel outlets restricted outflows and the resulting highest level of reservoir surcharge above the normal full supply level, El. 576.7 during the PMRF was 0.7 m. The full supply level was reached as early as mid-June and as late as mid-July.

(f) Flood Conditions at Kootenay Lake

Kootenay Lake is a natural reservoir which provides significant storage attenuation of flood flows. Inflows are the result of releases from the Duncan and Libby projects and natural local runoff from the Kootenay Lake tributaries, including tributaries between Libby dam and Kootenay Lake. The highest Kootenay Lake inflow of 7360 m³/s occurred in mid-June. The resulting peak outflow of 5660 m³/s and maximum Kootenay Lake level 3 m above the major damage elevation, El. 536.1, occurred 6 days after the inflow peak. These extremely high lake levels were caused by the need to release inflows at the Duncan and Libby projects because these reservoirs were full. For the PMRF event, Kootenay Lake outflows peaked at the end of July (3680 m^3/s), and the lake remained slightly above El. 536.1 for a period of 2 weeks. For the regulated PMUF event, levels above this elevation occurred for a period of 4 weeks.

C.3 FLOOD CONDITIONS DOWNSTREAM OF THE MURPHY CREEK PROJECT

The Probable Maximum Regulated Flood (PMRF) for the Murphy Creek project produced a peak discharge of 13 100 m^3/s at the end of July. The highest regulated peak flow in June was 11 000 m^3/s. As the reservoir storage capacity of the Murphy Creek project is small, these flows would be passed through the reservoir and would also occur at Trail. All extreme flood events with regulated peak discharges at Trail occurring after 1 May produced flows in excess of 7930 m^3/s (the major damage level at Trail) for periods from 5 to 27 days. For the PMRF events, flow levels close to the peak discharge of 13 100 m^3/s would occur for a period of 3 days.

The peak discharge during the PMRF (13 100 m^3/s) and the peak discharge for the PMUF (19 900 m^3/s) that could have occurred under pre-Treaty conditions, are plotted in Fig. C-9. This figure, showing PMF peaks versus drainage area, provides a comparison with other probable maximum flood studies.

C.4 SUMMARY

Flood control projects on the mainstem of the Columbia River upstream of the Murphy Creek project have more reservoir storage capacity to control extreme floods to non-damaging levels than flood control projects in the Kootenay River basin. The flow levels during the PMRF event produced major flood damage levels at Revelstoke for a period of 2 days or more but were passed through the Arrow Lakes Reservoir without surcharge above El. 440.7. During the same event, the Duncan Reservoir surcharged to a maximum level 0.7 m above the normal full supply level because the spillway was assumed to be unavailable.

Nearly all extreme flood events raised Kootenay Lake levels above the major damage elevation for a period of 1 to 4 weeks. The highest level of lake surcharge was 3 m above this elevation. Most of the extreme flood events produced peak flows at the Murphy Creek project site (and at Trail) above the 7930 m^3/s major damage level. The maximum regulated peak flow level of 13 100 m^3/s occurred at the Murphy site for a period of 3 days during the PMRF event.

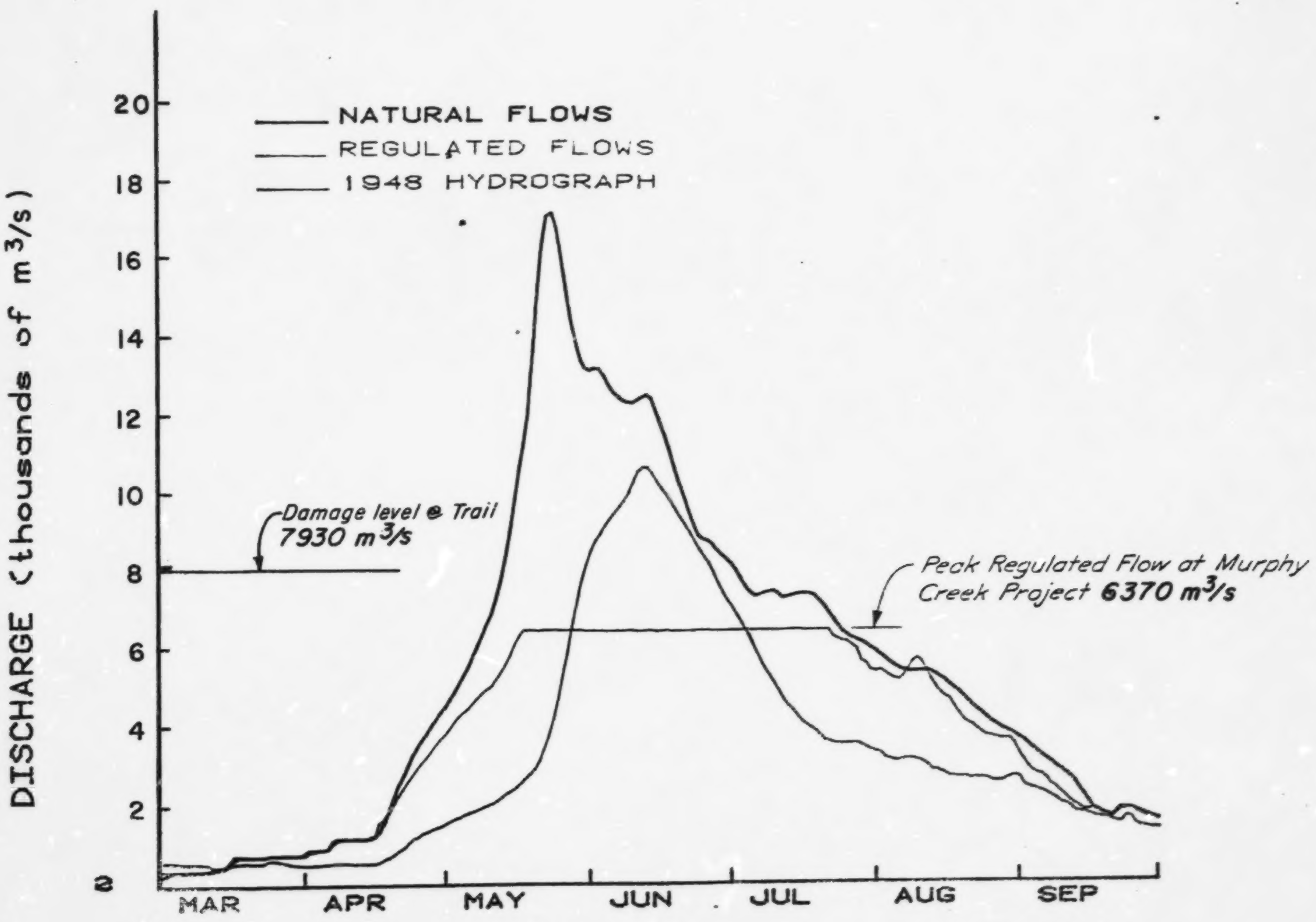


FIGURE C-1 HYDROGRAPHS AT MURPHY CREEK PROJECT - 72AP16MY16 SEQUENCE

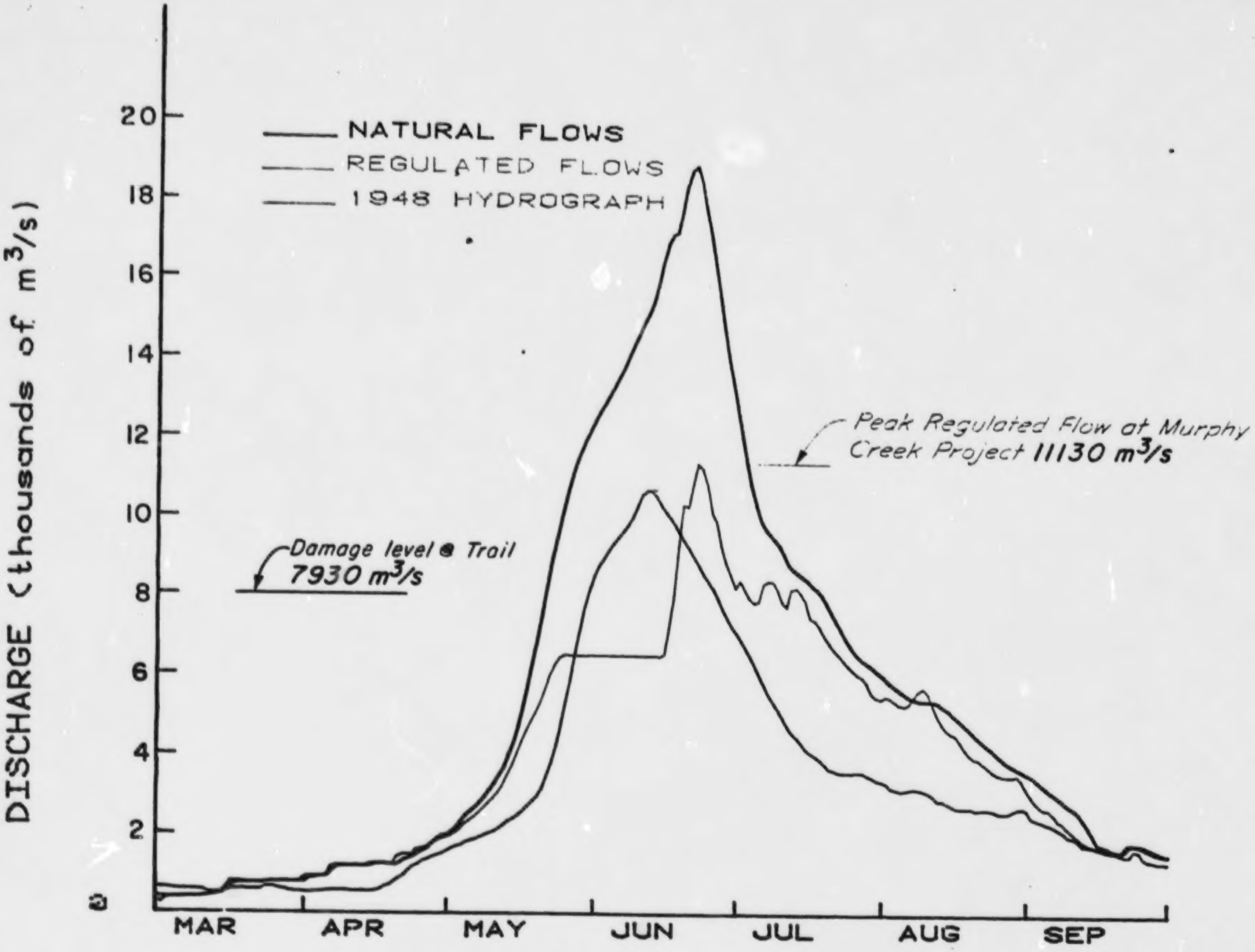


FIGURE C-2 HYDROGRAPHS AT MURPHY CREEK PROJECT – 72MY16JN15 SEQUENCE

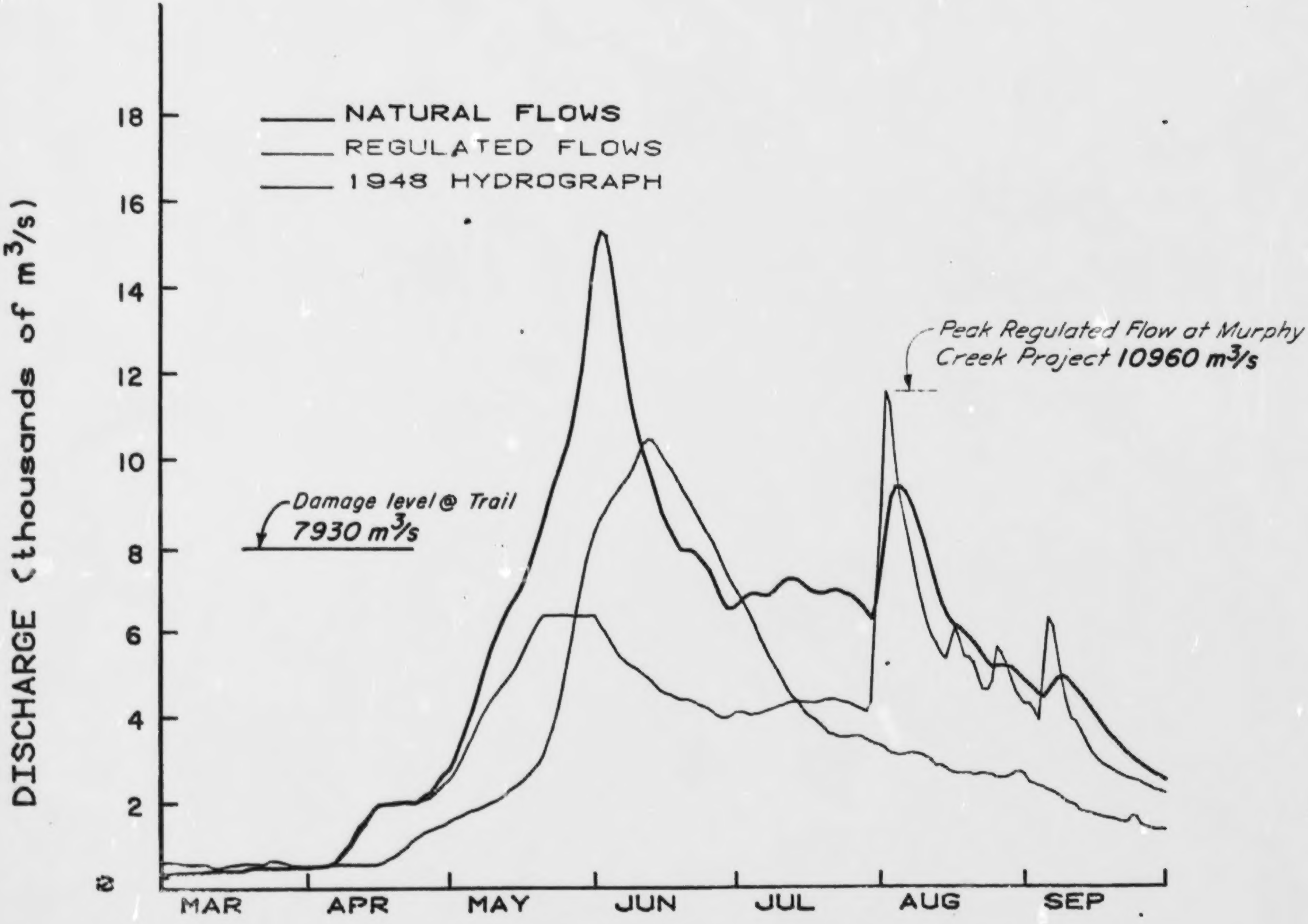


FIGURE C-3 HYDROGRAPHS AT MURPHY CREEK PROJECT - 76MY01JL27 SEQUENCE

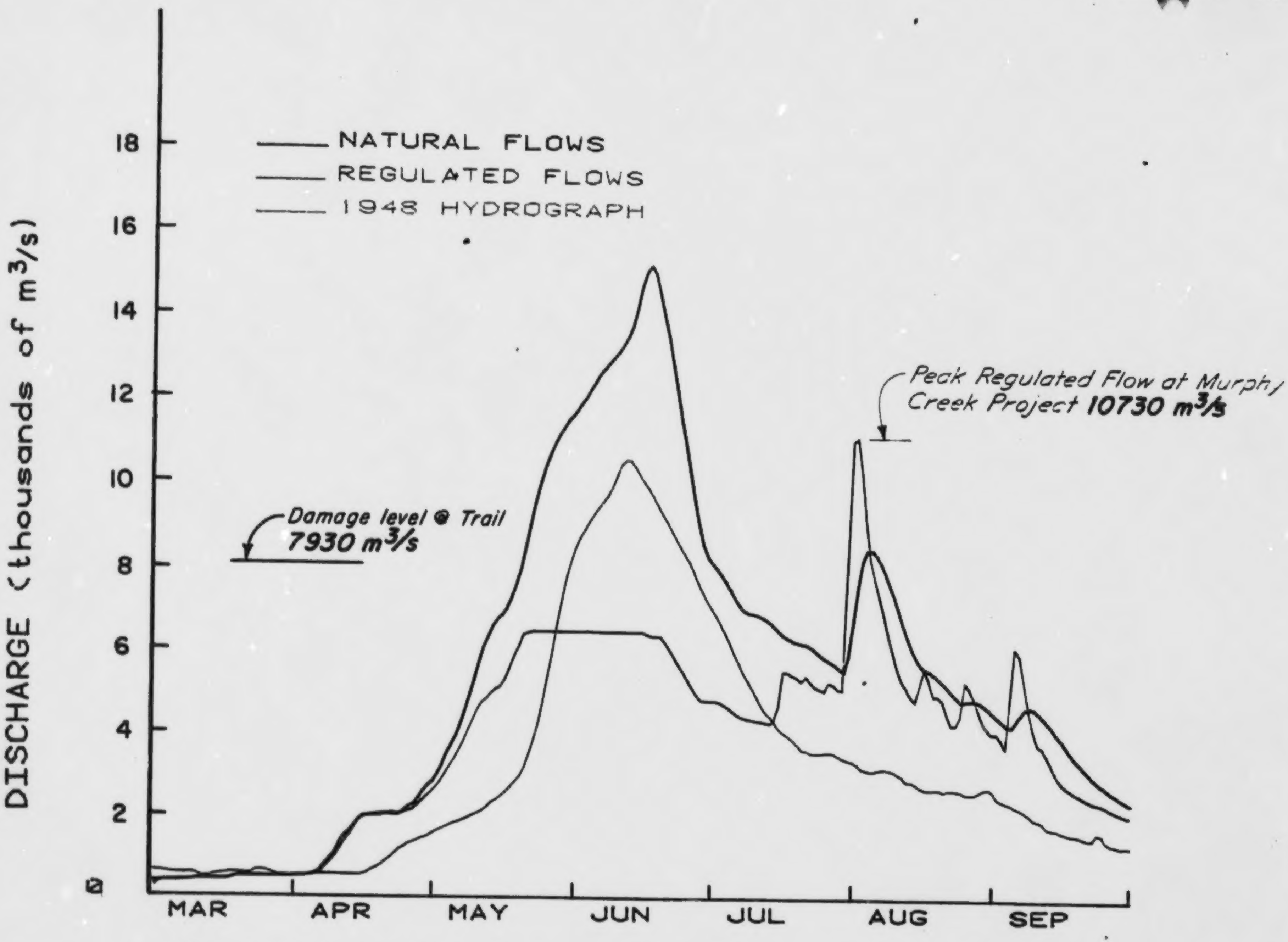


FIGURE C-4 HYDROGRAPHS AT MURPHY CREEK PROJECT - 76MY16JL27 SEQUENCE

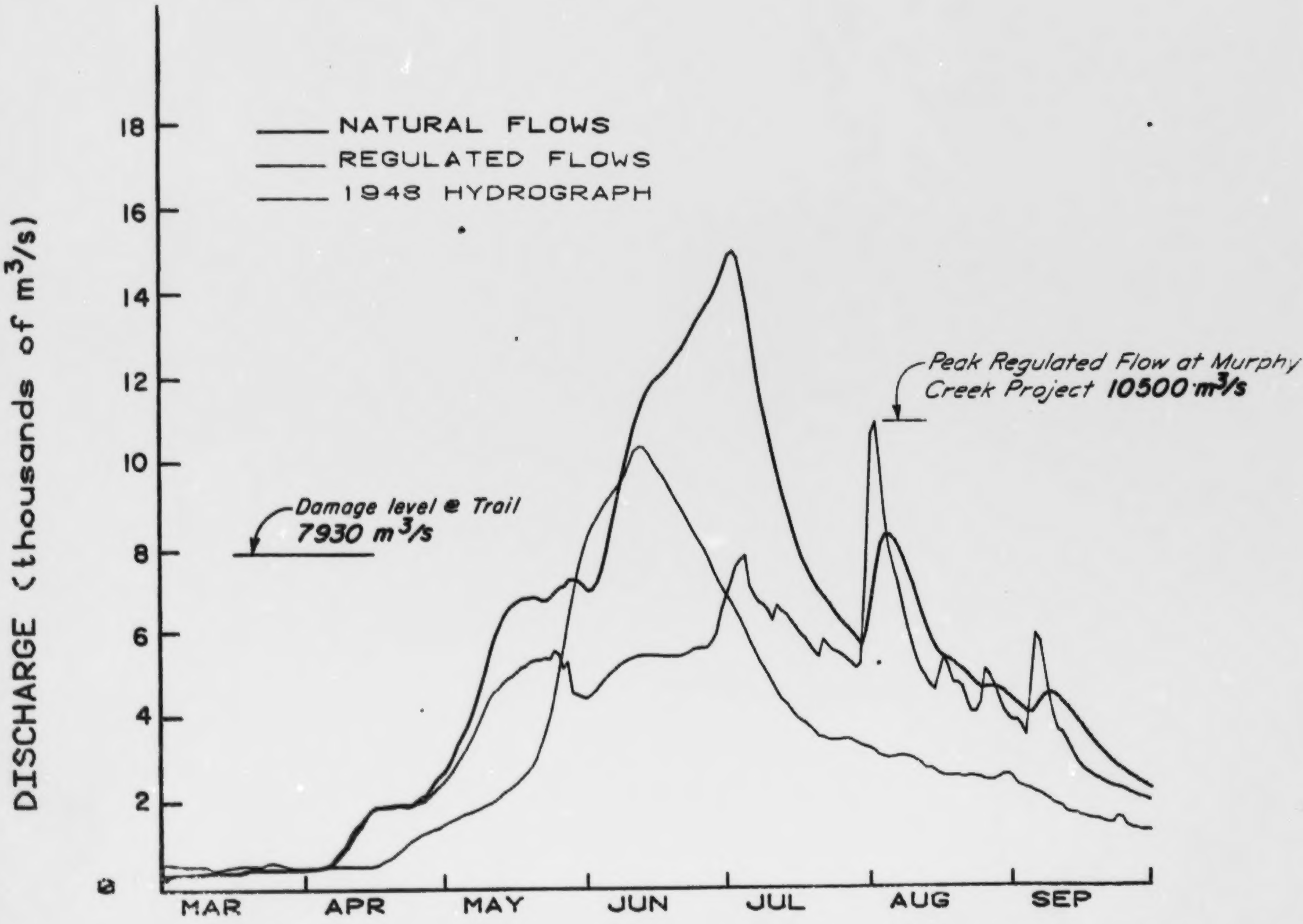


FIGURE C-5 HYDROGRAPHS AT MURPHY CREEK PROJECT - 76JN01JL27 SEQUENCE

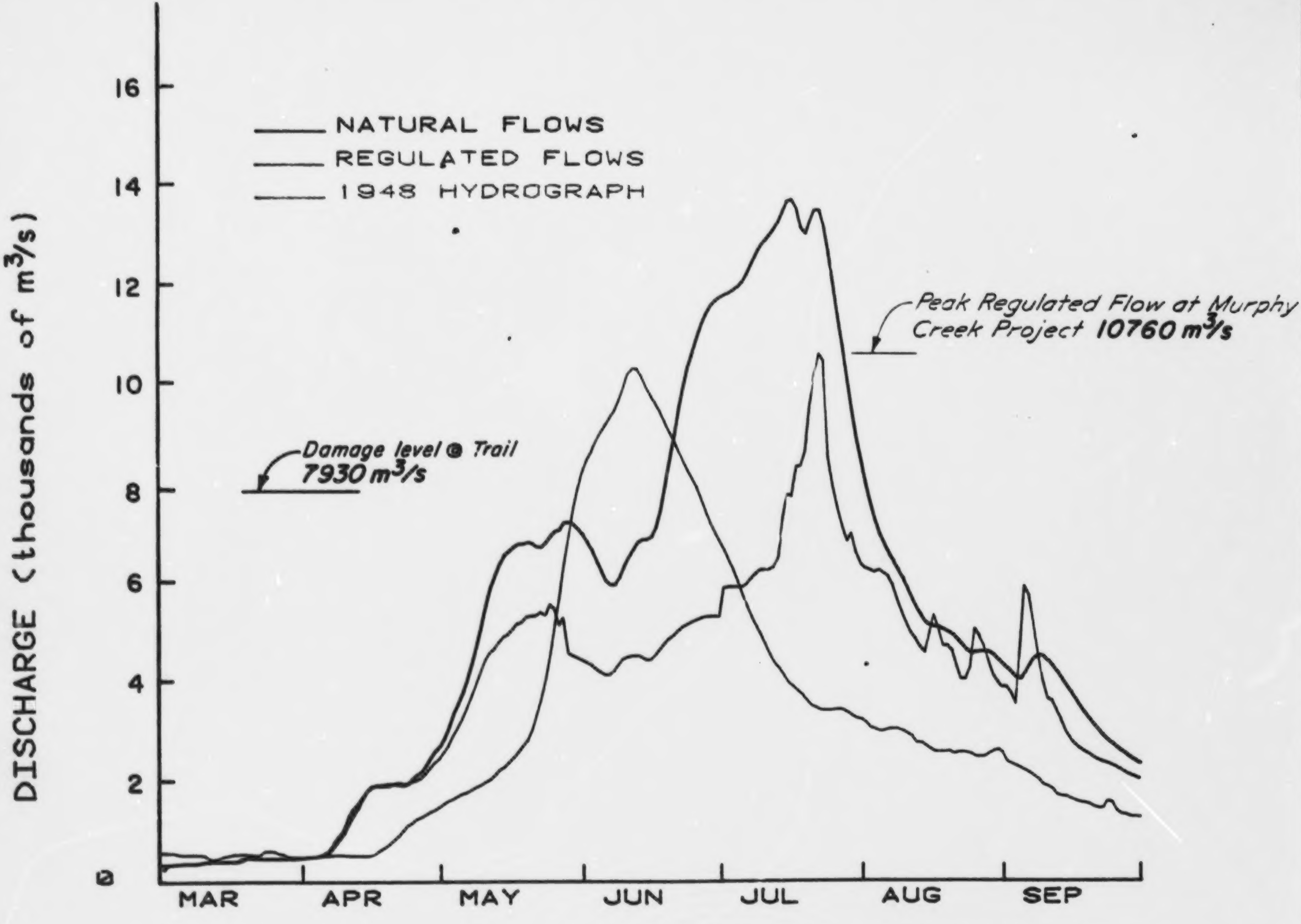


FIGURE C-6 HYDROGRAPHS AT MURPHY CREEK PROJECT - 76JN16JL16 SEQUENCE

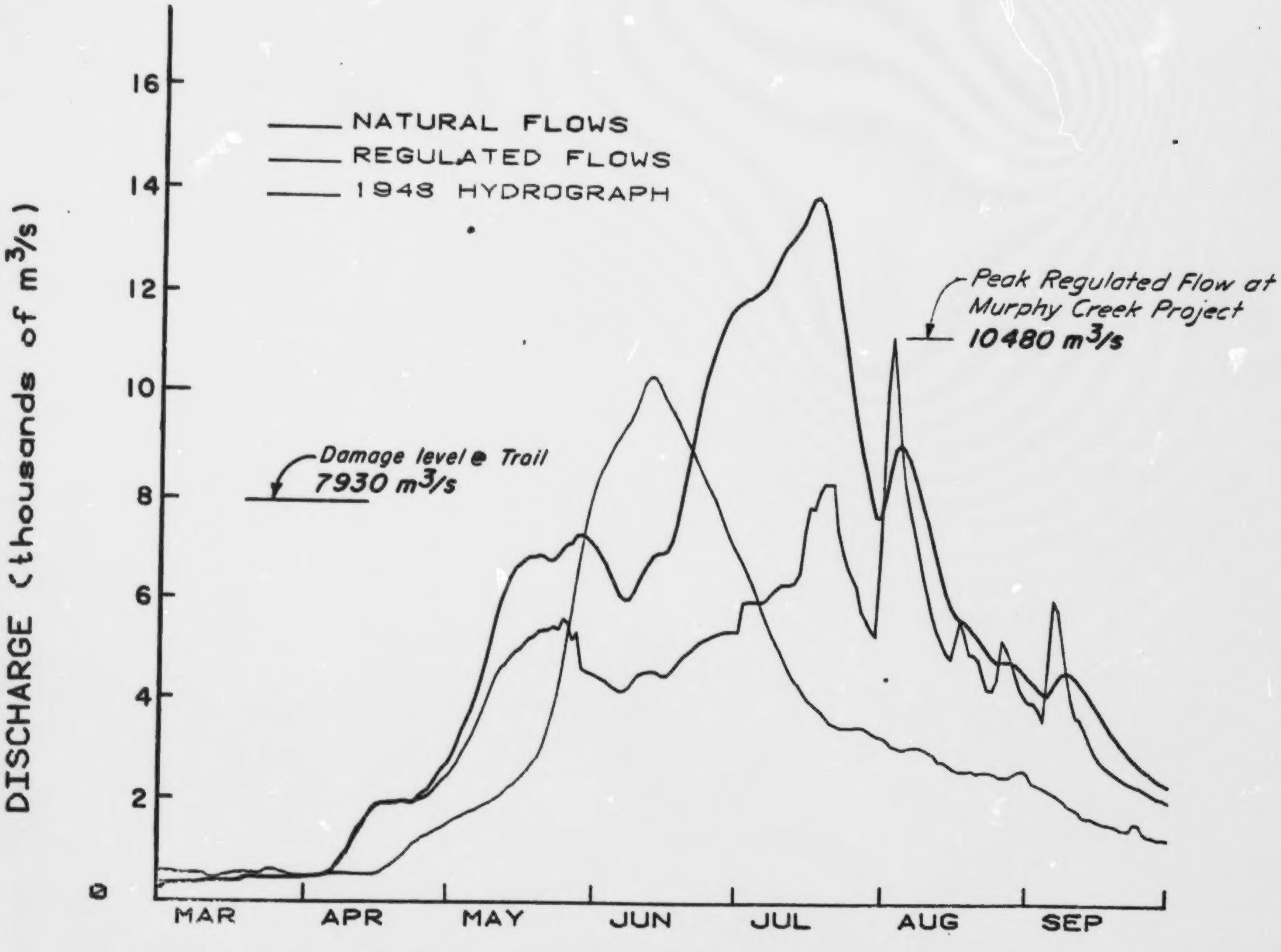


FIGURE C-7 HYDROGRAPHS AT MURPHY CREEK PROJECT - 76JN16JL27 SEQUENCE

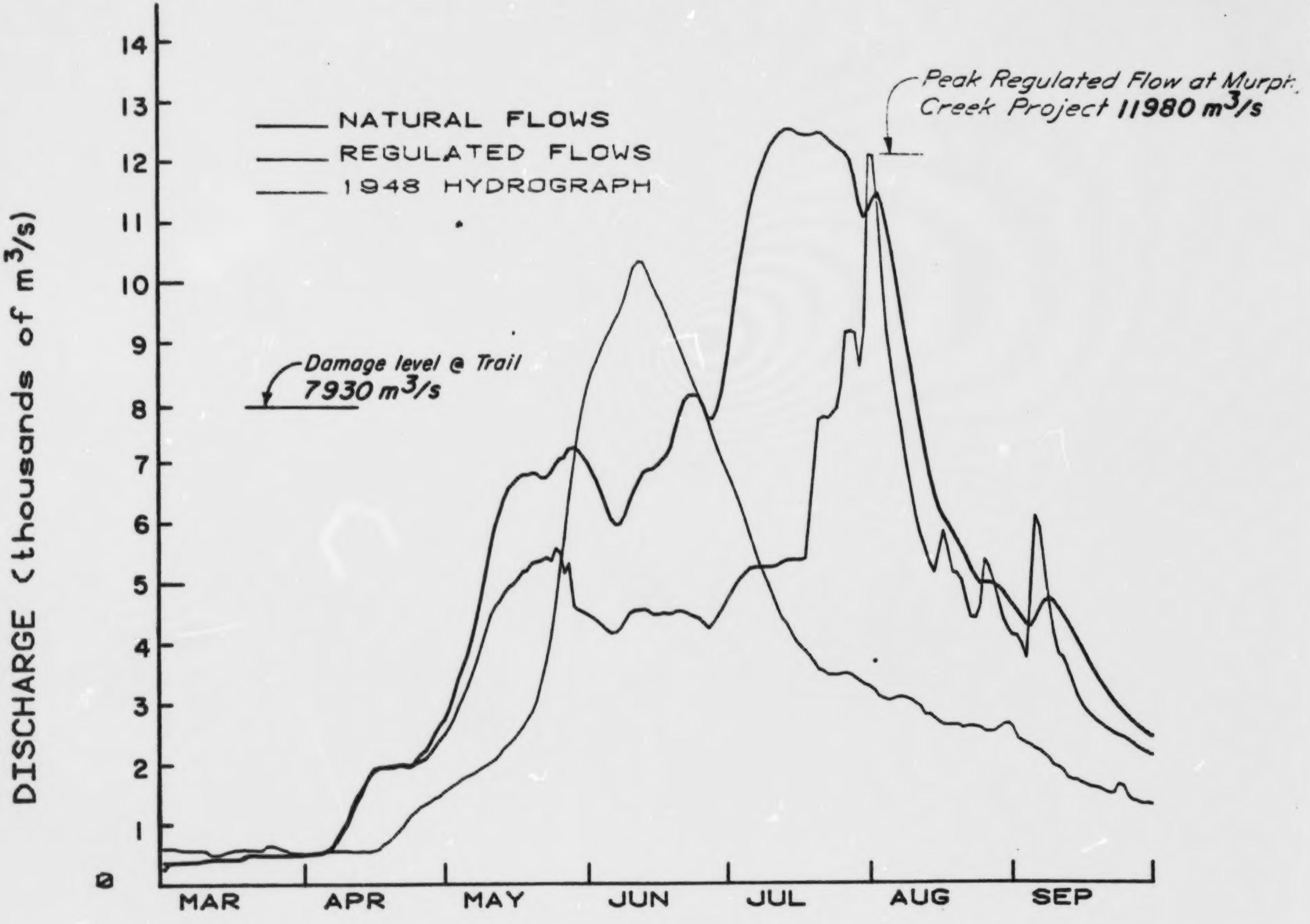
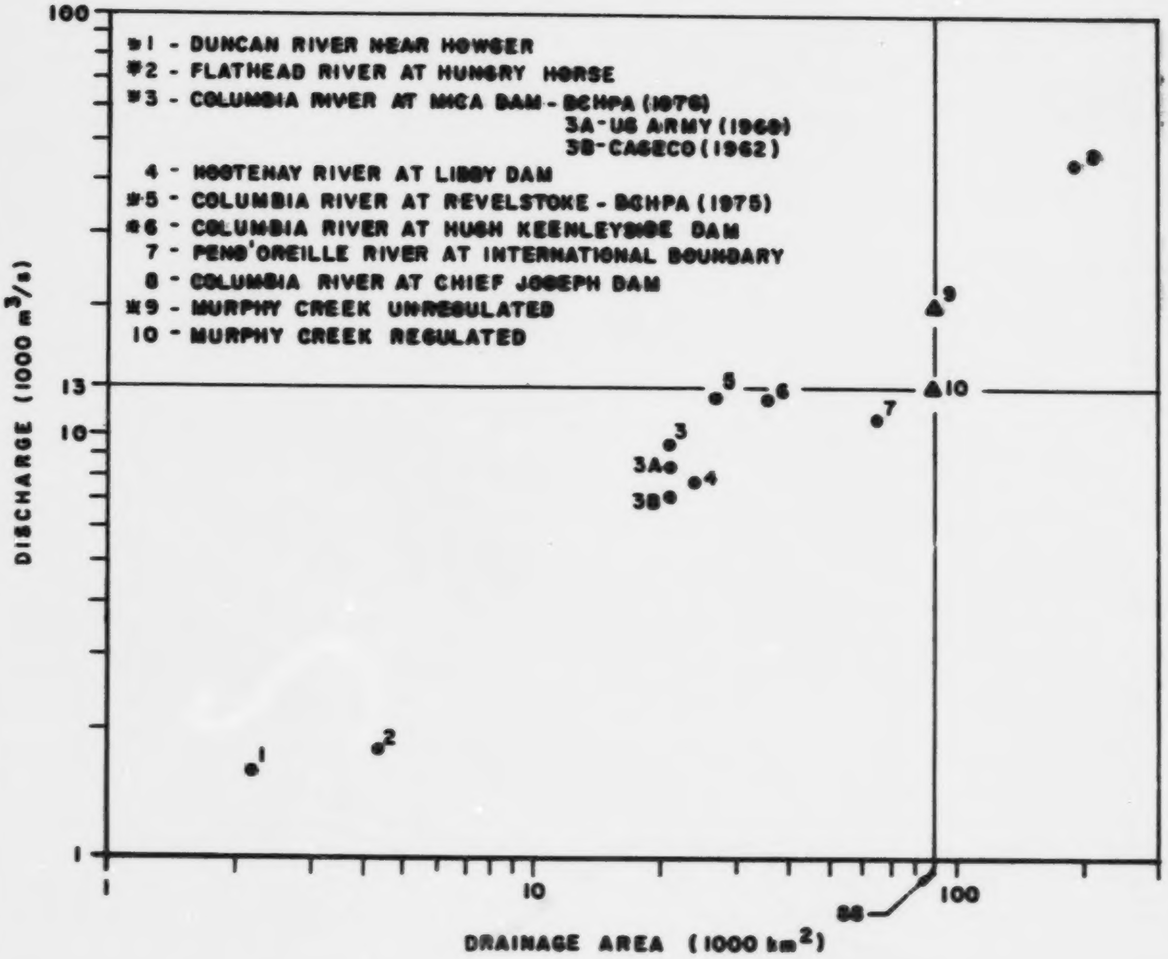


FIGURE C-8 HYDROGRAPHS AT MURPHY CREEK PROJECT - 76JN27JL27 SEQUENCE



* NATURAL CONDITIONS
(OTHERS REGULATED BY U/S STORAGES
OR UNKNOWN DEGREE OF REGULATION)

NOTE:

THIS FIGURE WAS REDRAWN FROM FIGURE 13 OF BCHPA REPORT 'REVELSTOKE (1880) PROJECT SPILLWAY DESIGN FLOOD', MARCH 1975

LEGEND:

▲ MURPHY CREEK PROJECT

● OTHER PROJECTS

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

COLUMBIA RIVER - MURPHY CREEK PROJECT

PEAK DISCHARGES OF ESTIMATED PROBABLE MAXIMUM FLOOD FOR DAM SITES WITHIN COLUMBIA RIVER BASIN

DATE 1983	FIG. C-9
DWN EC	DWG No.

REPORT No.

APPENDIX D

SEVERITY OF THE PROBABLE MAXIMUM FLOOD

APPENDIX D

WEVERITY OF THE PROBABLE MAXIMUM FLOOD

CONTENTS

Section	Subject	Page
D.1	INTRODUCTION	D - 1
D.2	MEASURES OF FLOOD SEVERITY	D - 1
D.3	SUMMARY	D - 7

TABLES

Table No.		
D-1	Murphy Creek Project - Maximized Floods	D - 3

FIGURES

Figure No.	
D-1	Columbia River Floods at Trail (Peak vs Volume)
D-2	Peak vs Volume for Maximized Floods at Trail
D-3	Peak vs Volume for July Floods at Trail
D-4	Seasonal Envelopes - Historical Floods at Trail
D-5	Seasonal Envelopes - Maximized Floods at Trail

APPENDIX D
SEVERITY OF THE PROBABLE MAXIMUM FLOOD

D.1 INTRODUCTION

The purpose of this Appendix is:

1. To compare the peaks and volumes of the most extreme possible (the maximized floods determined in the main report) to the peaks and volumes of floods observed at the Murphy Creek Project since 1913.

2. To produce the seasonal envelope of maximum flood peaks at the Murphy Creek Project site under pre-Treaty (1961) conditions and present-day (1981) conditions. The present-day conditions include the effect of the major flood regulation projects at Mica, Duncan, Arrow and Libby operated according to the 1972 Columbia River Flood Control Operating Plan.

3. To review the seasonally-dependent relationship between the maximum regulated peak discharges at the Murphy Creek Project and the operating procedures for passing the maximized floods through the upstream Treaty reservoirs.

D.2 MEASURES OF FLOOD SEVERITY

The severity of the maximized floods developed in the main report was investigated by comparing the peaks and volumes of these floods with the peaks and volumes of observed floods. The data was presented in different sections of the main report (Fig. 3-11 and Table 4-6) and has been reorganized for this Appendix. The observed (1913 to 1967) and estimated (1968 to 1977) floods were classified on the basis of their unregulated annual flood peaks (p), their April-August flood volumes (v) and by the ratio (p/v). These three flood characteristics are illustrated in Fig. D-1 for the floods at Trail between 1913 and 1977.

(a) Peak/Volume Ratios

The 1948 and the 1961 p/v ratios were shown to be the highest of record, and the upper p/v characteristic of observed floods was established by these two floods (line OX in Fig. D-1). Floods with the highest p/v ratios are produced by sequences of extremely high temperatures in early June which lead to high rates of snowmelt at that time. Floods with lower p/v ratios are produced by summer weather patterns that cause annual peaks in May or July. The June floods have the greatest potential for extremely high discharges at Trail because in this month, unlike May and July, there is the possibility for both a large available snowpack and an extremely high temperature sequence.

July floods (that is, floods with annual peaks occurring in July) are produced on average once in 7 years. July floods tend to be associated with the lower p/v ratios and these floods are separately identified in Fig. D-1. The most severe July flood peaks occurred on 19 July 1920 and 12 July 1954, and the upper p/v characteristic for the July floods was established by these events (line OY in Fig. D-1). The 1915 and 1976 p/v ratios were the lowest of record, and these floods established the lower p/v characteristic of observed floods (line ON in Fig. D-1).

The peak, date of peak and volume of the maximized floods developed in the main report are given in Table D-1, and their p/v co-ordinates are shown in Fig. D-2. The severity of the Probable Maximum Unregulated Flood (PMUF) is indicated by each of the three flood parameters - the peak p, the April-August volume v and the p/v ratio. For the PMUF event, each of these parameters is maximized.

The Probable Maximum Regulated Flood (PMRF) event has a significantly lower p/v ratio than the PMUF event because the peak of this event would occur in late July and early August after more of the snow has melted. This is nearly 2 months later than the peak of the PMUF event.

The other three maximized floods given in Table D-1 have p/v ratios which are above average and are similar to those of the major floods recorded in 1948, 1961, 1972 and 1974 and estimated for 1894. These historical floods appear to have had a potential for higher flood peaks which did not materialize because of the way in which the temperature sequences developed in those years.

(b) Flood Peaks

The effect of the Treaty reservoir operations on discharges at the Murphy Creek Project is to cause maximum regulated peaks to occur later in the flood season than they would have occurred under pre-Treaty unregulated conditions. In future, regulated peak flows will usually occur in late July or early August and the basin runoff potential at this time will be less than it is in June. The effective use of the Treaty reservoir flood control space will ensure that the potentially very severe unregulated flood peaks of June cannot occur. The capacity to regulate flood peaks under the most severe flood conditions is dependent upon the availability of the reservoir flood control space. Under the provisions of the Columbia River Flood Control Operating Plan, this space is developed during the winter and maintained through the reservoir refill period.

The actual regulation of peak flows depends on both the space made available in anticipation of summer flood conditions and the timing of the peak runoff. The peak flow reduction of each maximized flood and the 1894 flood is shown by the regulated peak discharge in Fig. D-2. The greatest peak flow reduction was achieved in May and early June when the reservoirs are only partially filled (U1; PMUF(U2)). Regulated August flood peaks were, in effect, unregulated because it was assumed that even under maximized runoff conditions the filling of the Treaty reservoirs would be completed by the normal 31 July refill date, and intentional use of reservoir surcharge space above the normal full pool operating levels would not be permitted. The highest regulated flood peak at the Murphy Creek Project was therefore produced by the Probable Maximum Rain event occurring at the end of July, immediately following reservoir refill.

The importance of the assumed restrictions regarding the use of reservoir storage space at the time during a PMRF event when the peak flow would occur, is indicated by the peak, volume and p/v ratio of the regulated flood at the Murphy Creek Project. For the PMRF event in early August these regulated flood parameters are maximized and this is illustrated in Fig. D-3. The maximized p-v characteristics of the two regulated July floods exceed the p-v characteristics of the unregulated historical floods. Thus, even with the utilization of $28 \times 10^9 m^3$ of Treaty storage, the peak reached during the PMRF at the Murphy Creek Project site will be more severe than the peak of any flood that has been observed in July.

(c) Flood Volumes

The 1894 flood volume is used as an indicator of extremely high runoff conditions which require additional upstream flood control space to reduce peak flows at The Dalles. This requirement is met by surcharging Arrow Reservoir between El. 440.1 and El. 440.7.

The Corps of Engineers estimated that the 1894 flood volume between 1 April and 31 August was 80 x $10^9 m^3$ at Trail. This can be compared to the recorded volumes which ranged between 31 x $10^9 m^3$ and 65 x $10^9 m^3$ and averaged 47 x $10^9 m^3$ during the 1913 to 1977 period of record. Under conditions of a maximized snowpack the historical temperature sequences result in an expected value of 85 x $10^9 m^3$ for the runoff volume with a maximum of 95 x $10^9 m^3$ during the PMUF. Even the most moderate (cool) historical summer weather would produce a runoff volume comparable to the 1894 event when maximized snowpack conditions exist. It can be concluded that large volumes of runoff should always be expected when large volumes of snow are resident on the watershed of the end of the winter. In Section 4-6 of the main report it was explained that adequate warning of an extreme flood would be provided by observed heavy snow accumulation prior to 1 April. It was therefore reasonable to assume that at least 28 x $10^9 m^3$ of reservoir storage space would be made available upstream of the Murphy Creek Project to control the ensuing large volume of runoff.

(d) Seasonal Flood Hydrograph Envelopes

The seasonal hydrograph envelope curve for the unregulated 1913 to 1977 flood flows at Trail, and the section of the estimated 1894 flood hydrograph that exceeds the envelope curves, are shown in Fig. D-4. The hydrograph envelope curve shown in Fig. D-4 is schematically represented in Fig. D-5 to emphasize the conclusion that maximized flood hydrographs greatly exceed those of recorded flows. Fig. D-5 also shows that under pre-Treaty conditions the PMUF peak could only occur in early June, and that under present-day conditions the PMRF peak can only occur in early August, immediately following the refill of the upstream Treaty reservoirs on 31 July. The PMRF peak of 13 100 m³/s in early August is more than twice the highest discharge (5660 m³/s) recorded at Trail after the 31 July refill date. This large increase in the August peak flow is contributed principally by the severity of the snowmelt and rainfall runoff leading to the PMRF peak. There is another contribution from the Arrow Reservoir regulation procedure incorporated into the analysis, which requires that surcharge be limited to El. 440.7 at that project. The effect of this operating procedure is to eliminate the natural regulation which was formerly provided by the Arrow Lakes before the Treaty.

Whenever the Arrow Reservoir is held at the full supply level, the Arrow Reservoir inflow and outflow hydrographs will be virtually the same, and the downstream hydrograph peaks at the Murphy Creek Project will slightly exceed the unregulated flood peaks that would have occurred under pre-Treaty conditions.

The situation at the Mica Project is similar to that at the Arrow Project in that once the storage has been filled the outflows will equal the inflows. In this analysis the assured refill requirement resulted in filling of the Mica Reservoir by 31 July and maintaining levels during the passage of August inflows. There would therefore be no attenuation of the unexpected Probable Maximum Rain event in early August; the contribution from the Mica Project to the PMRF peak at the Murphy Creek Project would be 4530 m³/s (without surcharge at the Mica Project). This is an extremely high flow from the Mica Project requiring operation of both the powerhouse and the outlet works in addition to the spillway and approaches the outflow during the Probable Maximum Flood at that project. The result is a PMRF of 13 100 m³/s at the Murphy Creek Project in early August.

Before 1 August, while the Mica Reservoir is filling, the assured refill criterion will result in releases of 280 m³/s from Mica during the early part of the refill period. This procedure ensures that high flows at The Dalles are not exacerbated by Mica releases during this early period when flood risks are high in the United States. Later when the flood risk in the U.S.A has diminished and the Mica Reservoir approaches the normal full pool operating level, releases may be increased as necessary to prevent premature refill. For example, the analyses here showed that releases of 1100 m^3/s in June and 2000 m^3/s in July would be required to delay refill until 31 July during the two highest unregulated floods, PMUF and U3 (Table D-1).

The increased Mica Project outflows, required to avoid premature refill in late June and mid-July, contributed to the June rise and high July level of the regulated flood peak envelope at the Murphy Creek Project (Fig. D-5). Probable maximum snowmelt and rainfall conditions occurring towards the end of June with the reservoir operation requirements could cause maximum regulated peak flows at the Murphy Creek Project to reach approximately 11 300 m^3/s between mid-June and 1 August.

D.3 SUMMARY

The PMRF at the Murphy Creek Project is sensitive to the way in which Mica storage is operated under the provision of the Treaty. Under all forecasted conditions of heavy runoff, such as the PMUF and the PMRF, it was assumed here that refill at Mica would be controlled to occur on the 31 July target date. Releases would be increased from the normal 280 m^3/s value of the early refill stages to as much as 2000 m^3/s in July. Under the provisions of the Columbia River Flood Control Operating Plan this type of operation avoids premature refill during flood conditions. This operating procedure limits the maximum probable discharge in June and July at the Murphy Creek Project to 11 300 m^3/s.

With full reservoir conditions after mid-August, maximum flows from the Probable Maximum Rain (PMR) event would not exceed 11 300 m^3/s because of the earlier depletion of the snowpack and the resulting recession of the snowmelt portion of the hydrograph. However, with recession continuing from the maximized late snowmelt, the maximum discharge at the Murphy Creek Project could reach as high as 13 100 m^3/s if, during the first 2 weeks of August, a PMR event occurs when the Mica Reservoir is full.

TABLE D-1

MURPHY CREEK PROJECT - MAXIMIZED FLOODS

Weather Sequence	Notation (for Fig. D-2)		UNREGULATED FLOOD			REGULATED FLOOD (28 x $10^9 m^3$ of live storage utilized at upstream Treaty projects)		
	Unregulated Flood	Regulated Flood	Apr-Aug Runoff Volume ($10^9 m^3$)	Peak Daily Discharge (m^3/s)	Date	Apr-Aug Runoff Volume ($10^9 m^3$)	Peak Daily Discharge (m^3/s)	Date
72 AP16 MY16[*1]	U1	R1	92.5	16 400	24 May	64.8	6 370	17 May to 21 Jul
72 MY01 MY31	PMUF[*2](U2)	R2	95.0	19 900	8 Jun	67.3	9 500	14 Jun
72 MY16 JN15	U3	R3	94.0	18 000	21 Jun	66.1	11 100	22 Jun
76 JN16 JL16	U4	R4	90.0	13 600	16 Jul	62.2	10 800	22 Jul
76 JL07 JL27	U5	PMRF[*3](R5)	89.2	12 900	27 Jul	61.4	13 100	2 Aug

---

[*1] 72 AP16 MY16 - 72 refers to background weather data for 1972; AP16 refers to starting date of extreme temperature sequence; MY16 refers to starting date of Probable Maximim Rain event.

[*2] PMUF - The Probable Maximum Unregulated Flood

[*3] PMRF - The Probable Maximum Regulated Flood

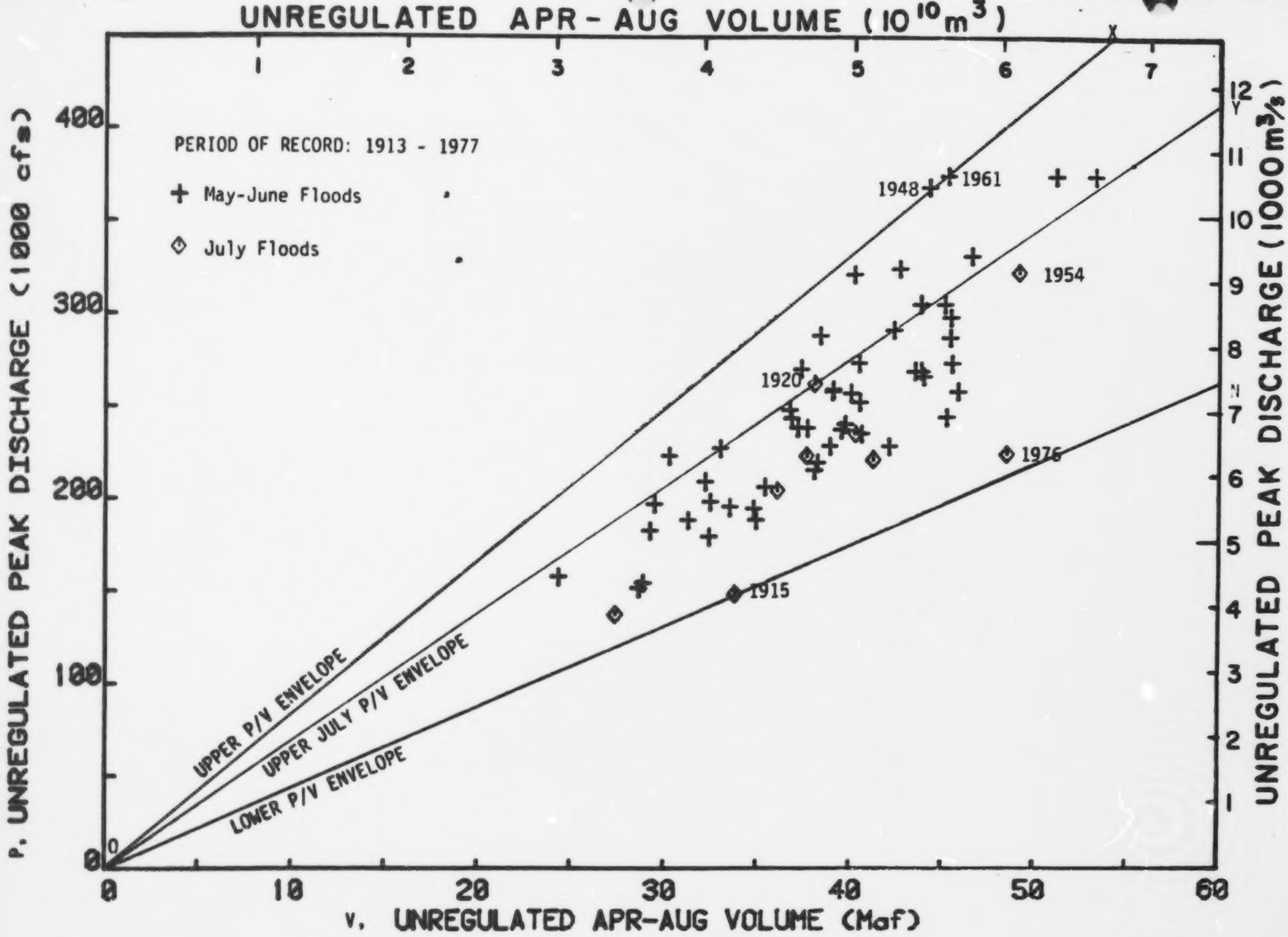


FIGURE D-1: COLUMBIA R. FLOODS AT TRAIL (PEAK vs. VOLUME)

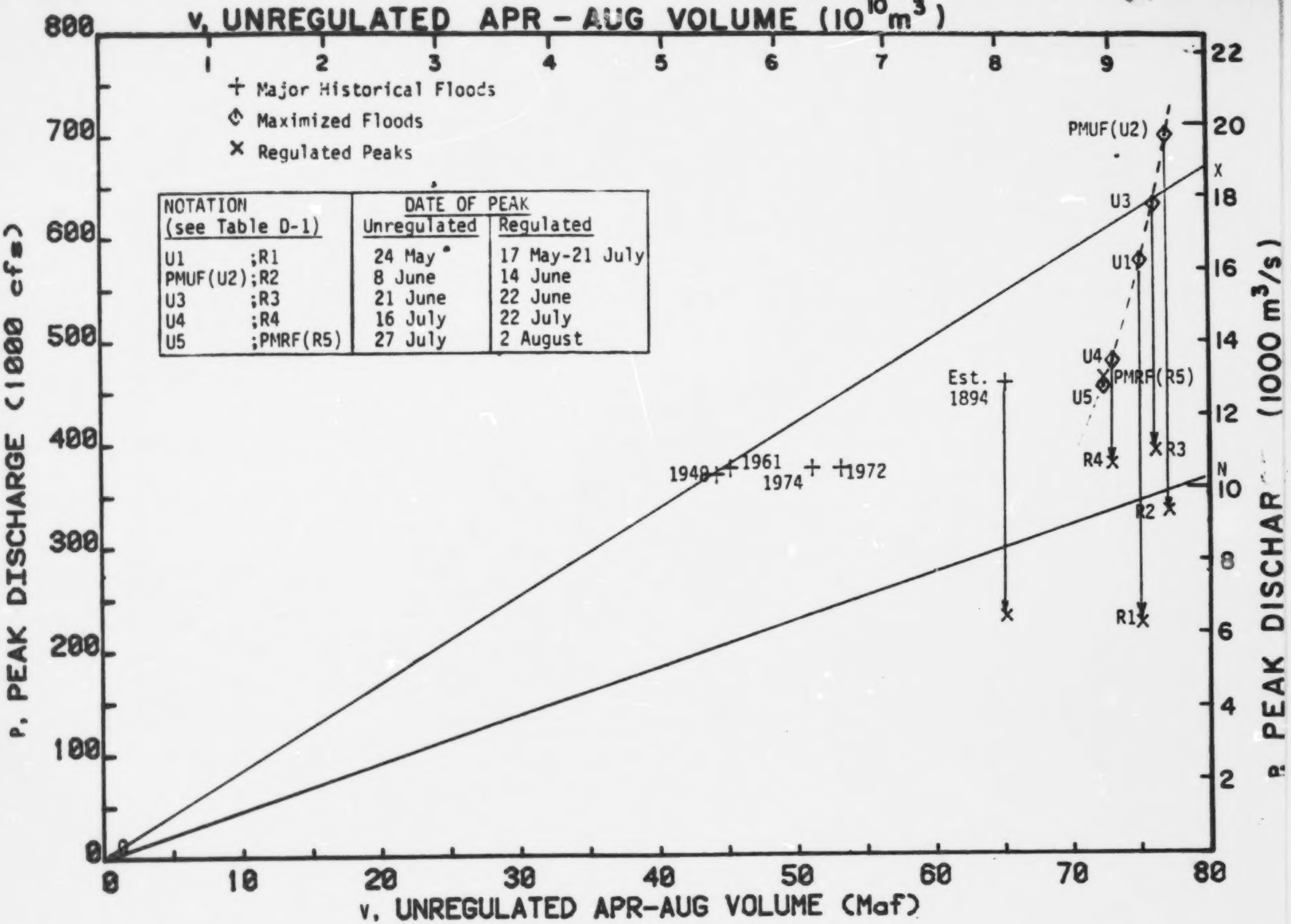


FIGURE D-2: PEAK VS. VOLUME FOR MAXIMIZED FLOODS AT TRAIL

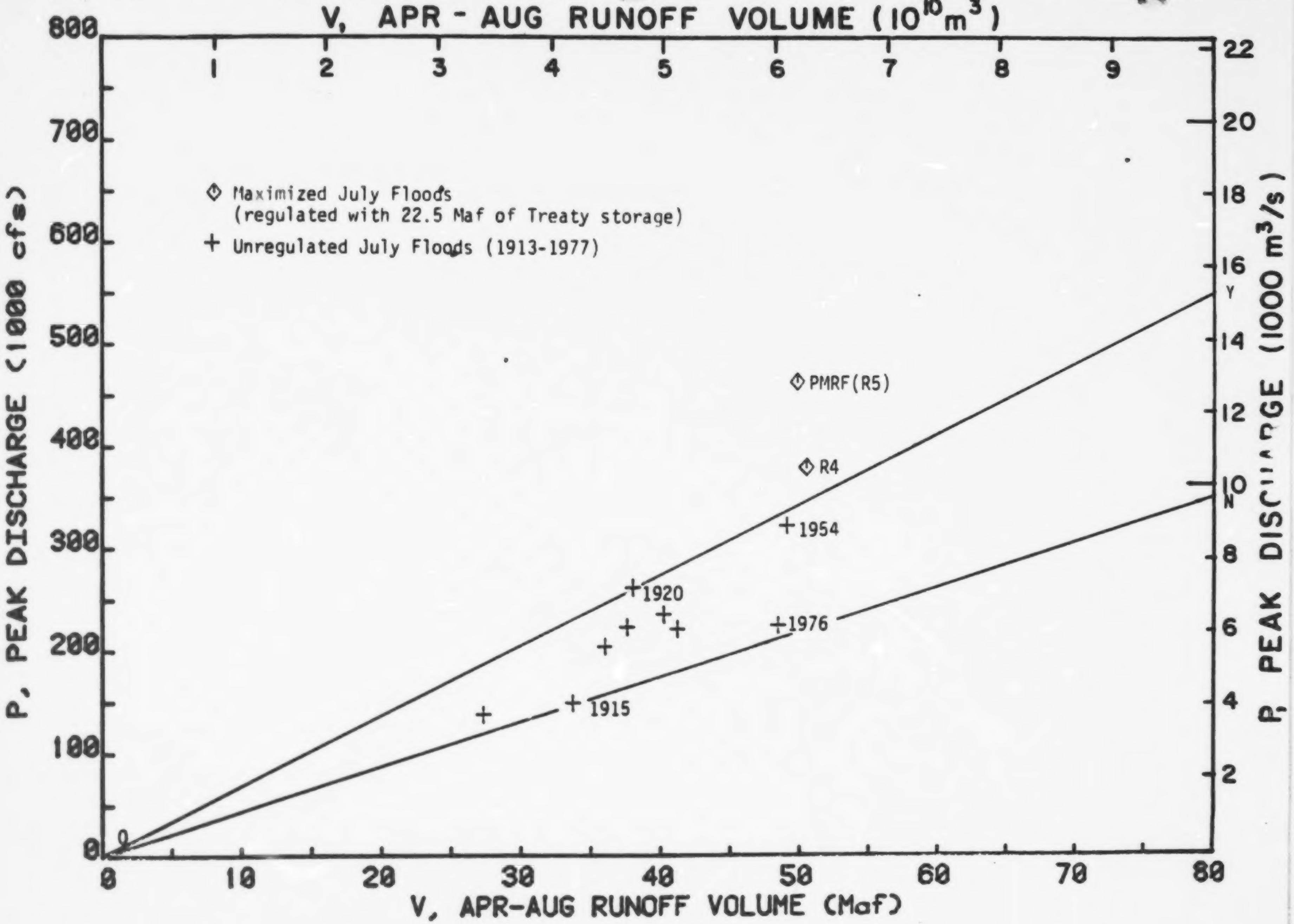


FIGURE D-3: PEAK VS. VOLUME FOR JULY FLOODS AT TRAIL

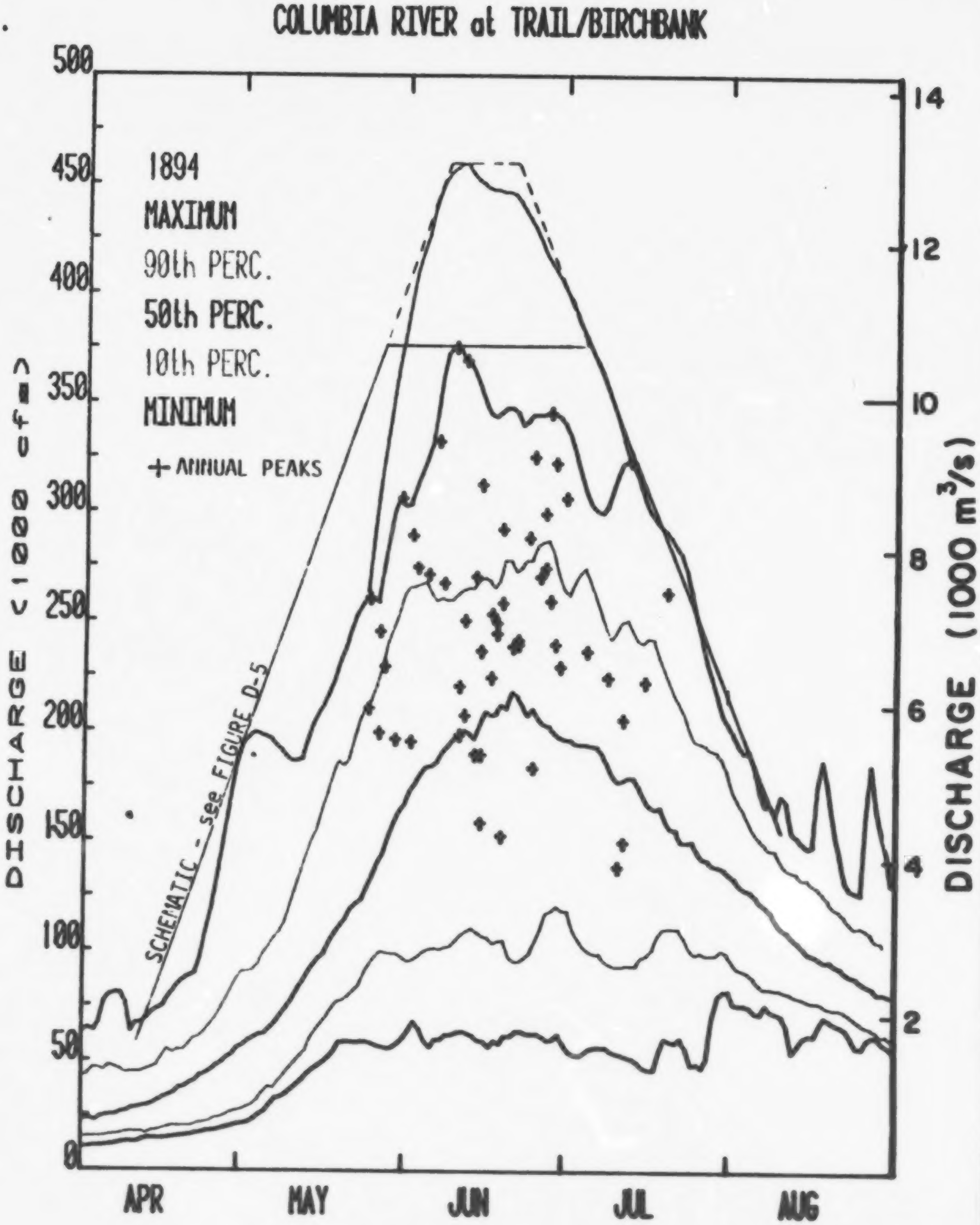


FIGURE D-4: SEASONAL ENVELOPES - HISTORICAL FLOODS AT TRAIL

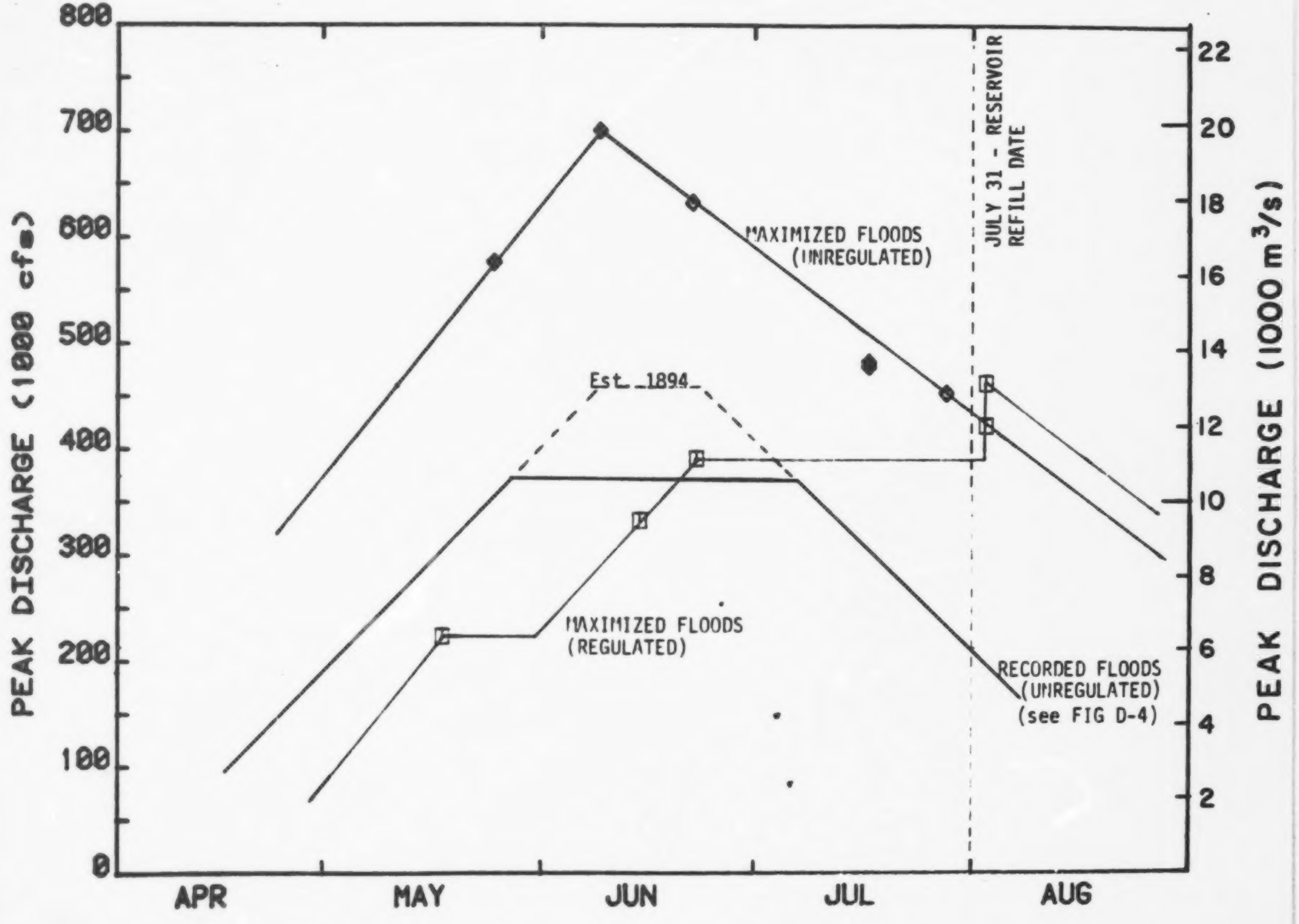


FIGURE D-5: SEASONAL ENVELOPES - MAXIMIZED FLOODS AT TRAIL

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2

BC
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P43
v.2
c.3

B.C. HYDRO

MURPHY CREEK PROJECT FLOOD STUDIES

VOLUME 2: DERIVATION OF THE REGULATED FLOOD FREQUENCY CURVE

HYDROELECTRIC GENERATION PROJECTS DIVISION

March 1983

AR72

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MURPHY CREEK PROJECT FLOOD STUDIES
VOLUME 2: DERIVATION OF THE REGULATED FLOOD FREQUENCY CURVE

March 1983

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HYDROELECTRIC GENERATION PROJECTS DIVISION
DEVELOPMENT DEPARTMENT

AR72

Report No. H 1598

MURPHY CREEK PROJECT FLOOD STUDIES
VOLUME 2: DERIVATION OF THE REGULATED FLOOD FREQUENCY CURVE

CONTENTS

Section	Subject	Page
	SYNOPSIS	iii
1.0	INTRODUCTION	
	1.1 Terms of Reference and Purpose	1 - 1
	1.2 Project Description	1 - 2
	1.3 Columbia River Treaty	1 - 3
	1.4 Previous Studies	1 - 6
	1.5 Outline of the Study	1 - 8
2.0	FLOOD FREQUENCY ANALYSES	
	2.1 Introduction	2 - 1
	2.2 Method of Analysis	2 - 3
	2.3 Unregulated Flood Frequency Curve	2 - 4
	2.4 Possible Regulation Assumptions and Resulting Flood Frequency Curves	2 - 5
	2.5 Summary	2 - 9
3.0	FLOOD SIMULATION ANALYSES	
	3.1 Introduction	3 - 1
	3.2 Method of Analysis	3 - 1
	3.3 Regulation Assumptions	3 - 2
	3.4 Results	3 - 3
4.0	VALIDITY OF FLOOD FREQUENCY CURVE	
	4.1 Comparison of Frequency and Simulation Analyses	4 - 1
	4.2 Actual Regulation since 1968	4 - 2
	4.3 Sensitivity of Design Floods to Treaty Flood Control Operations	4 - 3
	4.4 Sensitivity of Design Floods to Modified Operating Regimes	4 - 5

CONTENTS - (Cont'd)

Section	Subject	Page
5.0	CONCLUSIONS AND RECOMMENDATIONS	
	5.1 Conclusions	5 - 1
	5.2 Recommendations	5 - 3
	REFERENCES	

TABLES

Table No.	
2-1	Flood Frequency Peaks at the Murphy Creek Site
3-1	Simulated Flood Peaks at the Murphy Creek Site

FIGURES

Figure No.	
1-1	Map of the Columbia River Basin
1-2	Location of the Murphy Creek Project
2-1	Flood Frequency Curves at the Murphy Creek Site
4-1	Murphy Creek Project: Regulated Peaks versus Flood Volumes
4-2	Columbia River at The Dalles: Peak versus Seasonal Volume
4-3	Columbia River at Trail: Peak versus Seasonal Volume

SYNOPSIS

The purpose of this study was to derive the Regulated Flood Frequency Curve (RFFC) at the Murphy Creek Project site. The RFFC will be used to select the Diversion Design Flood (DDF) and the Spillway Design Flood (SDF) for the project. The DDF would determine the capacity of the river diversion works during construction, and the SDF would be used in the design of the project spillway to provide adequate flood level protection at Castlegar. The SDF was defined as the 200-year return period flood, 7590 m^3/s (268 000 cfs), and the DDF was tentatively selected as the 30-year return period flood, 6310 m^3/s (223 000 cfs).

The Columbia River Treaty ensures that $19.1 \times 10^9 m^3$ (15.5 Maf) of storage development in the Canadian portion of the Columbia River basin would be guided by an assured plan of operation, both for power and flood control. It was established that the mode of operation of the Treaty storage would be a major factor determining the flood risk at the Murphy Creek Project.

A key element of the present study was the determination of how operational constraints could lead to storage refill prior to the normal 31 July target date. Constraints considered in this study were the 95 percent confidence of refill requirement for Canadian Treaty storage, possible outflow restrictions at the Mica Project during the refill period, the effect of errors in forecasting seasonal runoff, and the relative importance of targetting flood control objectives along the main stem of the Columbia River.

The results of this study were based upon the regulated flood peaks that could occur when the storage was refilled. The flood risk at the Murphy Creek Project was shown to be sensitive to the date of refill of storage, which depends on whether Treaty storage at the Mica Project would be used in May-June for flood control in the U.S. or in July for flood control in Canada.

The Murphy Creek Project flood frequency curve was shown to be a composite relationship, and is developed from constituent curves that separately represent the project flood risk under various conditions of basinwide flood risk. The study also examined the validity of the flood frequency curve through flood simulation analysis, which investigated limitations that could arise from the selection of the 1913-1979 period of record for flood frequency analysis.

SECTION 1.0 - INTRODUCTION

1.1 TERMS OF REFERENCE AND PURPOSE

The terms of reference for the Murphy Creek Project flood studies (Volume 2: Derivation of the Regulated Flood Frequency Curve) were outlined in a letter to B.C. Hydro from Mr. A. Pipes, P. Eng. and Dr. M.C. Quick, P. Eng., dated 10 July 1980. The assignment consisted of the following items:

1. An evaluation of the key assumptions required to determine the flood frequency curve for use in establishing the Spillway Design Flood and the Diversion Design Flood for the Murphy Creek Project.

2. An assessment of the probable accuracy of runoff forecasts used in Columbia River Treaty operations and the impact that errors in these forecasts could have on the flood frequency curve.

3. An examination of the use of flood storage space at the Columbia River Treaty project reservoirs (Mica, Keenleyside, Duncan, Libby) during the regulation of 30 to 200-year volume floods.

The criteria selected for the preliminary design of Murphy Creek Project were the following:

1. The spillway would be designed to pass the Probable Maximum Flood (PMF) while ensuring the structural integrity of the project. (The PMF of 13 100 m^3/s (464 000 cfs) was established in the project PMF study.[1])

2. The spillway would be designed to pass the Spillway Design Flood, defined as the 200-year return period flood, with adequate flood level protection at Castlegar.

3. River diversion works for the project construction period would be designed to pass the Diversion Design Flood (DDF), tentatively selected as the 30-year return period flood, safely.

The PMF for the project was derived earlier in a separate report.[1] The objective of the present study is to determine the regulated flood frequency curve, which will be used to determine the SDF and DDF for the project.

1.2 PROJECT DESCRIPTION

The site of the proposed Murphy Creek Project is located on the Columbia River about 3 km upstream of Trail and 25 km downstream of Castlegar, which is at the confluence of the Columbia and Kootenay rivers. The drainage area above the project site is 88 000 km², which includes the entire Kootenay River drainage area in the United States and Canada and the upper Columbia River watershed. The long-term average discharge at the project site (1913-79) is approximately 2020 m³/s (72 000 cfs), and the reservoir formed by the project would have a small storage capacity of 145 x 10^6m³ (59 000 cfs-days), less than an average day's inflow.

The present development of the Columbia River basin includes three major projects (Mica, Revelstoke (presently under construction) and Keenleyside) on the Columbia River upstream of the Murphy Creek Project site, two major projects (Duncan and Libby) and five run-of-river plants in the Kootenay River basin, 11 plants on the Columbia River in the United States and 21 projects on other tributaries. A map of the Columbia River basin is shown in Fig. 1-1, and the location of the Murphy Creek Project is shown in Fig. 1-2.

1.3 THE COLUMBIA RIVER TREATY

The Columbia River Treaty of 17 January 1961 provided for the effective regulation of flow from the Canadian portion of the Columbia River basin for flood control and increased hydroelectric power production in the United States and Canada. The downstream power benefits resulting from the increased generation in the United States are shared by the two countries. In addition, the United States compensated Canada for the flood protection it received.

Under the Treaty, the Canadian Entity (B.C. Hydro) provided $19.1 \times 10^9 m^3$ (15.5 Maf) of effective flood storage space from two dams on the main stem of the Columbia River at Mica Creek and at the outlet of Lower Arrow Lake, and from one dam near Duncan Lake in the Kootenay River basin. The $19.1 \times 10^9 m^3$ of Canadian Storage ($8.6 \times 10^9 m^3$ (7.0 Maf) at the Mica Project, $8.8 \times 10^9 m^3$ (7.1 Maf) at the Keenleyside (Arrow) Project, and $1.7 \times 10^9 m^3$ (1.4 Maf) at the Duncan Project) approximately doubled the storage available in 1961 for the regulation of the flows of the Columbia River.

Under the terms of the Treaty, the United States Entity also provided $6.2 \times 10^9 m^3$ (5.0 Maf) of usable storage at the Libby dam on the Kootenai River in northern Montana. The total flow regulation capacity provided by the Treaty upstream of the Murphy Creek Project is therefore $25.3 \times 10^9 m^3$ (20.5 Maf).

An essential feature of the Treaty was that the development of the Canadian portion of the Columbia River basin would be based upon an assured plan of operation, both for power generation and flood control. Therefore, the Canadian Entity agreed to operate $19.1 \times 10^9 m^3$ of Canadian Storage in accordance with operating plans designed to achieve optimum power generation in Canada and the United States. Accordingly, Assured Operating Plans (AOP's) for Canadian Storage, and studies to determine the resulting downstream benefits, must be determined 5 years in advance of their implementation. Thus, for the 60-year life of the Treaty, AOP's are known for each of the next 5 years following the current operating year.

The Canadian Entity also agreed to operate 10.4 x 10^9m^3 (8.45 Maf) of the 19.1 x 10^9m^3 Canadian Storage for the purpose of flood control. This amount of flood control storage is sufficient to meet United States flood control needs in most years, and is defined as Primary Storage. In the original Treaty documents, the allocation of this flood control storage to the Canadian projects was 0.1 x 10^9m^3 (0.08 Maf) at the Mica Project, 8.8 x 10^9m^3 (7.1 Maf) at the Keenleyside Project, and 1.5 x 10^9m^3 (1.27 Maf) at the Duncan Project. An exchange of 2.5 x 10^9m^3 (2.0 Maf) of flood control storage between the Mica and Keenleyside projects was subsequently agreed upon as being equally effective for the control of floods on the Columbia River at The Dalles, Oregon.

It was estimated that the required power demand during each winter would normally lead to the evacuation of considerably more than 10.4 x 10^9m^3 of the 19.1 x 10^9m^3 of Canadian Storage. However, the United States Entity required the assurance that, when necessary, all of the storage at the Mica Project would be evacuated and would be available for the control of major floods. Therefore, the Canadian Entity agreed to operate additional storage (above the 10.4 x 10^9m^3 of Primary Storage) for flood control if called upon to do so by the United States Entity.

The conditions under which the United States Entity could call for additional flood control space were established by the Protocol to the Treaty. The Protocol established that only a major flood would require that more than 2.5 x 10^9m^3 of Primary Storage at the Mica Project be specifically operated for flood control. Secondary flood control space is referenced in the Treaty as 'On Call' storage.

Under the Treaty, 'On Call' storage can be requested only for 'potential floods' which have at least a 5 percent probability of producing a regulated peak discharge at The Dalles in excess of 17 000 m^3/s (600 000 cfs). The analysis to determine this forecast regulated flow must be based upon the use of all storage facilities which existed or were under construction in the United States portion of the drainage basin in January 1961, as well as storage at the Libby Dam and the Primary (flood control) Storage provided in Canada. It was estimated by the United States Entity that the use of the above storage would assure a reduction of about 8500 m^3/s (300 000 cfs) in the unregulated peak of major floods at The Dalles. Accordingly, it was estimated that a natural peak of 25 500 m^3/s (900 000 cfs) could be regulated to 17 000 m^3/s, which is the flood control objective (for major floods) at The Dalles.

It should be noted that most of the 'On Call' storage is located at the Mica Project, which has the facilities to evacuate up to 14.8 x $10^9 m^3$ (12.0 Maf) of storage space. An additional 2.5 x $10^9 m^3$ of "On Call" storage is located at the Keenleyside Project, and future "On Call" storage will be available upon completion of the Revelstoke Project. Only 8.6 x $10^9 m^3$ of this storage was provided under the terms of the Columbia River Treaty, and the United States Entity benefit entitlements are based upon this amount of storage at the Mica Project. The evacuation of more than this amount of storage for flood regulation should occur quite infrequently.

The Primary Storage (for flood control) amounts to 54 percent of the total Treaty storage in Canada and to 41 percent of the usable storage at the Mica, Keenleyside and Duncan projects. Current AOP studies show that, with the regional power demand, 8.6 x $10^9 m^3$ of Canadian Storage at the Mica Project would be evacuated on average one year in four. Thus, the flood protection provided by the Primary Storage is likely to be enhanced frequently by winter power generation and the resulting evacuation of storage at the Mica Project.

1.4 PREVIOUS STUDIES

Previous studies have demonstrated that the selection of the flood criteria for the design of the Murphy Creek Project can significantly affect the economic feasibility of the project.

(a) 1972 B.C. Energy Board Study[4]

No allowance was made in the Energy Board studies for the upstream regulation of flood flows that would result from the normal operation of the Columbia River Treaty projects.

The 1972 B.C. Energy Board study assumed that the spillway should be designed to pass all flows up to 11 300 m^3/s without raising the water levels at Castlegar above the normal full pool level. A further assumption was that the spillway should be designed to discharge flows exceeding 11 300 m^3/s without causing flood levels to be greater than they would have been under pre-project conditions. Meeting these criteria resulted in a very large spillway structure and approach channel, and a relatively high project cost.

(b) 1976 B.C. Hydro Land Reserve Study[5]

The impact of Treaty reservoir operations on the design of the Murphy Creek Project was first considered in the 1976 B.C. Hydro Land Reserve Study for the Murphy Creek and Border projects. Estimates of the peak flow reduction which would have been realized with the Treaty projects in operation were reported for 12 of the years in the 1913 to 1974 period of record. Estimates of these peak flow reductions were based upon the key assumption that in each of the 12 years, the 1972 Columbia River Treaty Flood Control Operating Plan[5] would dictate reservoir operations.

The results of the study showed that implementation of the Flood Control Plan could effectively control all 1913 to 1974 flows at Trail to less than 6370 m^3/s (225 000 cfs). In addition, the study showed that operation of the Treaty storages would have reduced the 1894 flood to a regulated peak discharge at Trail of 6540 m^3/s (231 000 cfs). The return period of the estimated natural peak of the 1894 flood of 13 000 m^3/s (459 000 cfs) at Trail was shown to be about 200 years.

Recommended revisions to the land reserve elevations for the Murphy Creek Project were based upon the assumption that the project spillway would be designed to pass a 'normal maximum flood' of 7930 m^3/s, equivalent to the flood protection objective at Trail adopted in the 1972 Columbia River Treaty Flood Control Operating Plan. The normal headpond water levels would therefore be exceeded only during the passage of very major floods. A regulated flood peak of 7930 m^3/s was considered to have a return period of greater than 200 years, but its return period was not determined.

(c) 1978 B.C. Hydro Prefeasibility Study[6]

For this study the spillway was designed to provide complete flood protection at Castlegar for the 200-year regulated flood, which was provisionally estimated, for the purposes of design, to be 7930 m^3/s. For this design, water levels at Castlegar during the passage of floods greater than 7930 m^3/s would have been higher than those prior to the Murphy Creek Project. The project design substantially reduced the Murphy Creek Project costs that were previously based on the results of the 1972 B.C. Energy Board Study.

(d) 1981 B.C. Hydro Probable Maximum Flood (PMF) Study[1]

The extreme flood conditions that would produce regulated flood peaks of greater than 7930 m^3/s at the Murphy Creek Project were identified in the project PMF study. In the study, it was shown that the use of 'On Call' storage would be requested, in accordance with the 1972 Columbia River Flood Control Operating Plan.

It was assumed that the refill of all Treaty reservoirs would be completed by the 31 July target date specified by the Treaty, and shown that the Probable Maximum Flood (PMF) of 13 100 m^3/s (464 000 cfs) would occur in early August.

1.5 OUTLINE OF THE STUDY

The regulated flow regime at the Murphy Creek Project is derived from the inflows to the Treaty project reservoirs and to unregulated areas, and from the storage regulation produced by the operation of the Columbia River Treaty projects (Mica, Keenleyside, Duncan, Libby).

The results of this study were based upon the observation that the annual peak flows at the project site would occur after upstream reservoirs had been refilled. The key to the derivation of the regulated flood frequency curve was, therefore, the determination of the date of refill at the Treaty projects. It was further established that effective flood control at the project site would be dependent upon the effective use of storage on the main stem of the Columbia River (and not the Kootenay River). Since storage refill at the Keenleyside Project is normally designated for flood peak reduction at The Dalles in May and June, effective flood protection in the Castlegar/Trail area in July must be largely derived from storage operations at the Mica Project. It was therefore possible to confine the analysis to the evaluation of July and August operations at the Mica Project.

Different operational constraints on the evacuation and refill of upstream storage were examined, and the effect of these constraints were systematically applied in the selection of peak flow data for regulated flood frequency analysis. It was recognized that the circumstances under which different constraints would apply would depend upon the flood risk in each year, and that, in some years, the constraints imposed by basinwide flood control operations would be applicable.

A major element of the study was the determination of how the operational constraints could lead to storage refill prior to the normal 31 July target refill date. (The completion of reservoir refill by 31 July is not actually stipulated by the Treaty. Instead refill by this date is needed to maximize the United States system firm energy load carrying capability. Most operating plans therefore include reservoir refill by 31 July to prevent the loss of downstream benefits from becoming too large.) Constraints considered in this study were the 95 percent confidence of refill requirement for the evacuation of the $19.1 \times 10^9 m^3$ of Canadian Treaty storage, possible outflow restrictions at the Mica Project during storage refill (as incorporated in the 1972 Columbia River Treaty Flood Control Operating Plan), and possible errors in procedures for forecasting seasonal runoff volume. The study also took account of contingency operating procedures that are outlined in the Flood Control Plan. These additional measures would be implemented under major flood risk circumstances to reduce the basinwide flood hazard, and to meet the established flood control objectives at Castlegar/Trail. Minor damage at Castlegar/Trail was recognized in the 1972 flood control plan to occur when the Columbia River flow exceeded 6370 m^3/s, and the adopted major flood control objective was 7930 m^3/s.

Another aspect of the study was developed because of the potential limitations of the 1913-1979 streamflow record used for flood frequency analysis. These limitations arise because the three largest floods in the last 100 years are known to have occurred in 1880, 1887 and 1894.

It is reasonable to infer from the 1879-1979 Columbia River flow record at The Dalles that the three largest floods in the Murphy Creek Project drainage basin also occurred in 1880, 1887 and 1894. Flood simulation analyses were undertaken to assess the potential importance of floods of this higher magnitude to the determination of flood risk at the Murphy Creek Project. By simulating the Treaty project inflows that would have resulted from combinations of recently recorded winter snowpacks and summer weather conditions, it was possible to reproduce flood events at the Murphy Creek Project site of a higher magnitude than has been observed in the 1913-1979 record. These hypothetical flood events were then analyzed to assess their regulation potential.

SECTION 2.0 - FLOOD FREQUENCY ANALYSES

2.1 INTRODUCTION

It will be demonstrated in this section that the Murphy Creek Project flood frequency curve is a composite relationship, developed from segments of both low and high flood risk regulated flood frequency curves at the project site. The constituent curves are developed in this section from a common 1913-1979 Columbia River streamflow record at Birchbank/Trail.

The operational considerations that complicate the derivation of the project frequency curve can be attributed to the restrictions that would be imposed whenever 'On Call' storage at the Mica Project is specifically used for flood control at The Dalles. The range in the potential flood risk at the project site is indicated by the constituent curves. This range in the flood risk is produced by different sets of operating assumptions concerning the regulation of Canadian Treaty storage, the impact of systematic error in the forecasting of inflow volumes to the Mica Project, and flood control objectives at different locations along the Columbia River. Each of the sets of operating constraints can be shown to be valid for certain return period ranges of flood risk.

Under conditions of low basinwide flood risk it was determined that the Assured Operating Plan (AOP) (for power) would provide a flexible and effective framework for serving United States and Canadian flood control interests. With a low flood risk, it was estimated that storage refill could routinely be achieved within 24 to 48 hours of the 31 July target date. The possibility of achieving this refill schedule during the regulation of larger floods would depend upon the capability of forecasting techniques to accurately update estimates of the runoff volume residual during the May-July storage refill period, and upon the flexibility of AOP operations to accommodate changes in the Treaty project outflow schedules. The first of the three regulated flood frequency curves developed in this section was based on the timely refill of storage each year on the 31 July target date.

The regulated flood peaks that would occur at the Murphy Creek Project site under conditions of high basinwide flood risk were derived under the assumption that the 1972 Columbia River Flood Control Operating Plan would be implemented, and that the operation of 'On Call' storage would be determined by this flood control plan. This involved the assumption that under conditions of high basinwide flood risk, outflow restrictions during the refill period would induce storage refill prior to the 31 July target date. The advance in the refill date at the Mica Project was based upon the volume forecast made prior to the refill period and reduced to meet the 95 percent confidence of refill criterion.

The investigation of the Mica Project volume forecast procedure showed that a systematic bias in the forecast equation leads to the underforecasting of the volumes of major floods and the overforecasting of the volumes of minor floods. For major floods, this forecast error would further advance the date of refill of storage of the Mica Project unless the outflow restrictions were relaxed in the final stages of storage refill. Whether or not the advance in the date of refill would be tolerated would depend upon the increased potential for damage to downstream flood hazard areas.

It was determined that the failure to correct for the Mica Project forecast error would cause the established flood control objective at Castlegar/Trail to be exceeded at the 150-year return period level. This unacceptable result was regarded as an unintended consequence of implementing the 1972 Columbia River Flood Control Operating Plan. The result was directly attributed to the combination of the restrictive flood control refill schedule at the Mica Project, and the bias in the

1 April volume forecast procedure. The relaxation of the minimum outflow schedule during the final stages of storage refill in July would correct the adverse effect of the systematic forecast error and would be compatible with a more balanced interpretation of the flood control plan (equally serving United States and Canadian flood control objectives). Therefore, the regulation assumptions associated with the above regulated flood frequency curve were considered to be inappropriate.

A second high flood risk curve, based upon a more realistic operating assumption that the adverse effects of forecast error could be corrected in the final stages of storage refill (in July), was developed. This flood frequency curve was derived under the assumption that the volume inducing early refill would not exceed the standard (unbiased) volume forecast reduction. With this regulation assumption, the 200-year regulated flood peak at the project site was less than the major flood control objective at Castlegar/Trail. (It should be noted that the flood control limit is an operational threshold in every year, and it would be expected that storage operations would be modified when possible to ensure that the major flood control objective would not be unnecessarily exceeded.)

2.2 METHOD OF ANALYSIS

It was assumed that the Treaty dams were operational in each year of the 1913-1979 Columbia River flow record at Birchbank/Trail. A projection of the date of refill of Treaty storage was made and the natural flows at the Murphy Creek site (those which occurred or would have occurred with no Treaty dams operational) were then studied to determine the highest flow after the projected date of refill. This flow was selected as the peak regulated flow for that year.

For the pre-1967 period of record, recorded flows in late July and August were normally augmented to some extent by releases from upstream natural (lake) storage. Under present-day conditions, flows at the site would be slightly less than the observations during the period of record. Nevertheless, the conservative assumption was made that it would be necessary to discharge flows at the Murphy Creek Project equal to the recorded flows on the dates immediately following the projected date of refill for the upstream projects.

A frequency analysis of the annual peak regulated flows was made, and from this analysis, the regulated flood frequency curve was derived. Several statistical distributions, including the two- and three-parameter lognormal, Pearson III and Gumbel I, were tested to determine which provided the best fit for the peak flow data. The results given in this report are based upon the two-parameter lognormal distribution, and are very similar to results based on other distributions.

A review of the observed flood hydrographs indicated that the regulated flood frequency results would be very sensitive to the projected date of refill of upstream storage. Two methods of storage refill were analyzed, and the results are presented in Section 2.4. The unregulated (natural) flood frequency curve for the Murphy Creek site is developed in Section 2.3.

2.3 UNREGULATED FLOOD FREQUENCY CURVE

The unregulated (natural) flood frequency curve for the Columbia River at the Murphy Creek site was developed to serve as a basis for comparison with regulated flood frequency curves developed in the following section. The analysis is based upon the 1913-1979 period of record and shows the flood frequency curve under pre-1967 regulation conditions (no Treaty projects in place). It should be noted that the 7930 m^3/s major flood control objective at Castlegar/Trail established in the 1972 Columbia River Treaty Flood Control Operating Plan had a return period prior to the construction of the Treaty projects of less than 5 years. The curve is summarized below and is plotted in Fig. 2-1.

Return Period (years)	Unregulated Flood Peak (m^3/s)	Unregulated Flood Peak (cfs)
5	8 320	294 000
30	10 480	370 000
100	11 780	416 000
200	12 490	441 000
500	13 390	473 000

The mean unregulated flood peak for the 65-year sample is 7020 m^3/s (248 000 cfs). For this and all of the other flood frequency relationships given in this report, the 95 percent confidence band for an estimate is roughly equal to plus or minus 5 percent of the estimate at the 5-year return period level and plus or minus 10 percent of the estimate at the 200-year return period level.

2.4 POSSIBLE REGULATION ASSUMPTIONS AND RESULTING FLOOD FREQUENCY CURVES

(a) Treaty Storage Refill on 31 July

It was assumed that the Assured Operating Plans (AOP's) would provide an effective framework for achieving target date refill and for serving United States and Canadian flood control interests for all flood risk conditions. The validity of this assumption would depend upon short-term flood forecast capability in July, and upon the adoption of a more flexible storage operation of the Mica Project than is indicated by the 1972 Columbia River Treaty Flood Control Operating Plan. The storage operation achieving target date refill would have to produce the same level of flood control effectiveness at The Dalles as is provided by the existing flood control plan.

Treaty storage was assumed to refill at 2400 hours on 31 July of each year. In this case, the peak regulated flow for each year would be the highest recorded flow after 31 July. The curve is summarized below and is plotted in Fig. 2-1.

Return Period (years)	Regulated Flood Peak: 31 July Refill (m^3/s)	Regulated Flood Peak: 31 July Refill (cfs)
5	4 470	158 000
30	5 490	194 000
100	6 120	216 000
200	6 460	228 000
500	6 880	243 000

The above table shows that the regulated flood frequency curve based on a 31 July refill operation is approximately 50 percent lower than the unregulated curve. The average peak flow for the 31 July refill operation is 3960 m^3/s (140 000 cfs).

(b) Predetermined Flood Control Refill of Canadian Storage

It was assumed that the 1972 Columbia River Treaty Flood Control Operating Plan would be implemented to assure flood control, especially during the period of greatest flood risk at The Dalles (May/June). The implementation of the basin wide flood control plan would impose restrictions on the refill of 'On Call' storage at the Mica Project. It was assumed that the required headwater project refill strategy, requiring minimum project outflows until refill, would induce the refill of Canadian Storage prior to the 31 July target date. For this type of operation, the Treaty Storage would be refilled on a variable July date, determined by the 95 percent confidence of refill requirement (for the evacuation of Canadian Storage). It was determined that systematic errors in forecasting April-July flood volumes could further advance the refill date. No specific allowance was made to remedy July flood risks induced by refill ahead of the target date.

The procedure for determining the April-July runoff volume which would have been forecast each year on 1 April was based upon the accuracy of the forecasts produced by the Runoff Volume Forecast Program for the Canadian Treaty Reservoirs (VOLCAST)[7] for the years 1935-79. Forecast April to September volumes (as of 1 April) for each year were obtained from VOLCAST, and the recorded April-September volumes were calculated from records. The forecast and recorded April-September volumes were then pro-rated, using long-term average flows, to give estimates for the April-July period. A linear regression relationship was then obtained between the recorded and forecast volumes. To meet the requirements of a 95 percent probability-of-refill criterion, the linear regression relationship corresponding to the lower 90 percent confidence level (two-tailed test) was derived. (Five percent of the time, the runoff volume for the April-July period would be less than the value corresponding to this 90 percent confidence level.) Using this relationship, it was then possible to derive a reduced volume forecast, corresponding to any observed April-July runoff volume.

The reduced forecast of runoff volume for each year was then compared with the recorded runoff volume for that year. In almost all years, the recorded volume was higher than the reduced forecast volume. The difference between these two values was the excess water which would have been passed by the upstream projects between the date of refill and 31 July. Taking project minimum discharges into account, refill at the Mica Project would occur, on average, 7 days prior to the target date, 31 July. In years of high runoff, refill at Mica could occur up to 14 days ahead of the target date. (The variable refill dates at the Mica Project for the period 1947 to 1979 were obtained from recorded data near the project, and the refill dates for the period 1913 to 1946 were based on derived relationships using estimates of the Columbia River discharges at Castlegar.)

As before, the peak recorded flow at the Murphy Creek site after the computed date of Treaty storage refill for each year was taken to be the peak regulated flow for that year. The Flood Frequency Curve is summarized below and is labelled "Predetermined Flood Control" in Fig. 2-1.

Return Period (years)	Regulated Flood Peak: Uncorrected Forecasts (m^3/s)	(cfs)
5	5 290	187 000
30	6 820	241 000
100	7 760	274 000
200	8 270	292 000
500	8 950	316 000

It should be noted that the assumed operation of the Canadian Storage, including the failure to correct for flood forecast error, would cause the 7930 m^3/s major flood control objective at Castlegar/Trail to be exceeded at a 150-year return period level. This result was regarded as an unintended consequence of implementing the flood control plan. A second frequency curve was therefore developed (Updated Flood Control), based upon a more realistic operating assumption that the Mica Project outflow schedule could be increased in July to offset the adverse effects of flood volume forecast error.

(c) Updated Flood Control Refill of Canadian Storage

It was assumed that the 1972 Columbia River Treaty Flood Control Operating Plan would be implemented to assure effective flood control in Canada and the United States throughout the May-July flood risk period. It was further assumed that the headwater project refill strategy at the Mica Project would only be modified as required to ensure that the volume of water passed between the date of refill and 31 July would not exceed the standard volume forecast reduction (unbiased) accounting for the 95 percent confidence of refill. The relaxation of the minimum outflow schedule during the final stages of storage refill in July corrected the adverse effects of systematic forecast error. The revised refill schedule at the Mica Project can be shown to serve both Canadian and United States flood control interests. It specifically allowed for the targeting of the 7930 m^3/s major flood control objective of Castlegar/Trail. The average advance in the date of storage refill was reduced from 7 days (the previous frequency curve using the predetermined flood control refill of Canadian Storage) to 5 days.

The flood frequency curve is summarized below and is labelled "Updated Flood Control" in Fig. 2-1.

Return Period (years)	Regulated Flood Peak: Partially Corrected Forecasts (m^3/s)	(cfs)
5	4 950	175 000
30	6 310	223 000
100	7 130	252 000
200	7 590	268 000
500	8 150	288 000

2.5 SUMMARY

The circumstances under which the different regulation assumptions for Canadian (Treaty) Storage Operation would apply would depend upon the flood risk in a given year. For some years, the constraints imposed by major basin wide flood risks would be applicable. For the more frequent low flood risk years, however, flood control interests would automatically be accommodated through the implementation of AOP's. Table 2-1 provides a summary of the 30 and 200-year flood peaks under each of the regulation assumptions.

It is difficult to precisely define the frequency with which basin wide flood control difficulties would be experienced in early July, and the way in which July flood control problems at The Dalles would affect the storage refill at the Mica Project. Two possible modes of operation of 'On Call' storage at the Mica Project were considered and the difficulty in establishing the Murphy Creek Project frequency curve was overcome by deriving alternate regulated flood frequency curves for high and low conditions of basin wide flood risk (Section 2.4(a) and 2.4(c)). The Murphy Creek Project flood frequency curve is a composite of these frequency curves. The low return period range of the project frequency curve can be reasonably represented by the frequency curve devloped in Section 2.4(a), and the high return period range of the project frequency curve can be represented by the frequency curve developed in Section 2.4(c). For a limited return period range, the project frequency curve must be represented by a transition between these two curves.

It is important, when determining the DDF, that the return period range of the transition segment be established. This was done through the evaluation of the existing criteria that determine the need to implement the 1972 Columbia River Treaty Flood Control Operating Plan. This is discussed in Section 4.3.

TABLE 2-1

FLOOD FREQUENCY PEAKS AT MURPHY CREEK SITE

Flood Frequency Curve	30-year Return Period Flood (m^3/s)	200-year Return Period Flood (m^3/s)
Unregulated	10 480	12 490
Predetermined Flood Control	6 820	8 270
Updated Flood Control	6 310*1	7 590*2
AOP Target Date Refill:		
31 July	5 490	6 460

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*1 Tentatively selected as the Diversion Design Flood (DDF) for the Murphy Creek Project.

*2 Selected as the Spillway Design Flood (SDF) for the Murphy Creek Project.

SECTION 3.0 - FLOOD SIMULATION ANALYSES

3.1 INTRODUCTION

The main purpose of the flood simulation analyses was to evaluate the regulation approximations incorporated in the flood frequency analysis (Section 2.0). A second purpose was to determine whether the major regulated flood peaks derived in this section would be compatible with the Murphy Creek Project flood frequency curve.

A potential limitation of the 1913-1979 streamflow record at Birchbank/Trail was that the three largest Columbia River floods at The Dalles were known to have occurred in 1880, 1887 and 1894. It reasonably follows, then, that the annual floods at Birchbank/Trail in the same years were also the largest that occurred in the same period, and that the 1880 and 1887 July runoff from the Canadian portion of the basin exceeded the 1954 July record volume. Flood simulations reviewed in this section were based upon severe combinations of winter and summer weather observed between 1965 and 1978. Several of the simulated floods also generated greater volumes of runoff in July at the project site than was recorded in 1954. Through flood simulation, it was possible to examine the regulation of floods of this higher magnitude at each Treaty project site, and to examine the regulated flood hydrographs that would occur at the Murphy Creek Project site.

3.2 METHOD OF ANALYSIS

Hypothetical runoff conditions and the resulting regulated flood hydrographs at the Murphy Creek Project site were simulated through the use of the UBC Watershed Model[9] and the UBC Flow Model.[10] These models were calibrated during the PMF studies for the Murphy Creek Project.[1]

The snowpacks used in the model were the same for each simulation, and were similar to conditions observed on 1 April 1972 in the upper Columbia River drainage basin and on 1 April 1974 in the Kootenay River drainage basin. These snowpacks were estimated to have a return period of approximately 30 years. The meteorological data used in these simulations were taken from the period 1965 to 1978.

The flood runoff simulations, therefore, represent estimates of what would have actually occurred if, for example, the winter weather of 1971/72 was followed in sequence by the summer weather of 1975. Out of the 14 simulated runoff events the seven highest-volume runoff events (1967, 1968, 1969, 1970, 1972, 1975, 1976 weather) were selected and flood control regulation simulations were evaluated using the UBC Flow Model.

3.3 REGULATION ASSUMPTIONS

It was assumed that the evacuation of $25.3 \times 10^9 m^3$ of reservoir storage space at the Mica, Keenleyside, Libby, and Duncan projects would be completed prior to the flood control refill period. It was estimated that there would be a 95 percent probability of refill of this storage by 31 July. Flood simulation based upon the 1976 weather sequence showed that relatively low April-July inflows would occur and that the Canadian Storage at the Mica Project would be refilled by August only if a minimum outflow schedule was maintained through June and July. The schedule of Treaty project outflows during the refill period was based upon the runoff pattern produced by the cool, wet 1976 weather sequence. This weather pattern substantially delayed the occurrence of snowmelt runoff in the basin, and it was estimated that 95 percent of summer weather patterns would generate more runoff by the end of July (given the same initial snowpack conditions) than was simulated by the 1976 weather pattern.

For the purpose of this study, Treaty storage space in Arrow Reservoir would not be made available specifically to re-regulate high July outflows from Mica Project. It was assumed that the reservoir surcharge space between El. 440.1 m (1444.0 ft) and 440.7 m (1446.0 ft) would not be reserved for flood-control purposes. Therefore, following the refill of the Mica reservoir, there would be no guarantee of effective regulation of flows entering Arrow Reservoir. A review of actual Treaty project operations since 1967 showed that, in years of above-average runoff, Arrow Reservoir reached its normal full-pool operating level (440.1 m, or 1444.0 ft) by mid-July, and that the Kootenay River flows were normally in recession.

3.4 RESULTS

The simulations demonstrated that the Mica reservoir would be the last to be filled and that the regulated flood peaks at the Murphy Creek site would occur after the refill of the Canadian (Treaty) Storage. For six of the seven weather sequences, the April-July runoff volume at each of the Treaty projects exceeded the 95 percent confidence refill volume and contributed to premature reservoir refill at the project sites. In these simulations, the regulated peak occurred before the target refill date of 31 July. For the 1976 weather pattern, the upstream reservoirs filled on 31 July and the peak flow occurred after this date.

The results of the flood simulation analyses are given in Table 3-1. For the seven simulations, minimum outflows were discharged from the headwater Treaty reservoirs during the flood control refill period until the date of refill of those reservoirs. After that date, inflows to the projects were passed. For these simulations, the average peak flow at Murphy Creek site was 6680 m^3/s (236 000 cfs). The average peak regulated flow following the 31 July target date was 5210 m^3/s (184 000 cfs).

The analyses showed that the variation in summer weather could cause a wide range in the peak regulated flows at the project site. More significantly, the simulation results demonstrated that, given identical 1 April snowpacks, premature refill peaks in July could vary from 5520 m^3/s (195 000 cfs) to 8010 m^3/s (283 000 cfs), and peaks after 31 July could vary from 3370 m^3/s (133 000 cfs) to 6120 m^3/s (216 000 cfs). The maximum simulated flow occurring after the 31 July target refill date was 6120 m^3/s (216 000 cfs). This was produced by 1976 summer weather and occurred during a major rainstorm in September.

TABLE 3-1

SIMULATED FLOOD PEAKS AT THE MURPHY CREEK SITE

Snowpack Year	April to September Weather Sequence		Regulated Peak Flow (m^3/s)	Regulated Peak Flow After 31 July (m^3/s)
	Year	Type		
1972/1974*	1970	Hot	8010	3910
1972/1974	1975	Hot	7700	4700
1972/1974	1968	Wet	6850	5120
1972/1974	1972	Wet	6650	5410
1972/1974	1976	Wet	6120	6120
1972/1974	1967	Hot	6030	4670
1972/1974	1969	Hot	5520	3770

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* Combined snowpack using 1972 data for the Columbia River basin above Castlegar and 1974 data for the Kootenay River basin.

SECTION 4.0 - VALIDITY OF FLOOD FREQUENCY CURVE

4.1 COMPARISON OF FREQUENCY AND SIMULATION ANALYSES

The results of the flood frequency and flood simulation analyses are both illustrated in Fig. 4-1. This figure shows that the relationship between the regulated flood peaks at the Murphy Creek Project site and their associated April-August flood volumes is extremely variable. Fig. 4-1 is based upon the flood peak data derived in Section 2.4(c), i.e. the flood frequency curve based upon the Updated Flood Control Refill of Canadian Storage, and the regulated peak and volume data obtained in Section 3.3 through flood simulation analysis.

The relatively weak relationship between regulated flood peaks and volumes illustrated in Fig. 4-1 demonstrates the importance of other factors contributing to the flood risk at the Murphy Creek Project site. The regulated flood peak in a given year can be shown to depend upon the forecast flood volume, the seasonal distribution of runoff caused by the summer weather, and upon the use of flood storage space. The upper envelope of the regulated peak-volume relationship is produced by late (July) floods and the lower envelope is produced by early (May/June) floods.

The mean April-August flood volume for the historical data is $47.7 \times 10^9 m^3$ (38.7 Maf), and the mean volume of the simulated floods is $71.3 \times 10^9 m^3$ (57.8 Maf). It was estimated that the mean simulated flood volume would occur on average once in 200 years. The flood frequency curve established in Section 2.4(c) indicates that the return periods of the simulated flood peaks based upon 1970 and 1975 summer data would have return periods of between 300 and 500 years. This indication would be consistent with occurrence of the climatological factors contributing to these flood events.

The similarity between the regulated flood characteristics indicated by the two sets of data shown in Fig. 4-1 shows that the assumptions used in flood frequency and flood simulation analyses are compatible. Furthermore, the regulated peaks obtained through flood simulation analysis are compatible with the extrapolation of high flood risk frequency curve used for the derivation of the project design flood discharges.

4.2 ACTUAL REGULATION SINCE 1968

The results of actual flood regulation since 1968 are summarized in Figs. 4-2 and 4-3. It was estimated that floods with April-August volumes equal to that of the 1972 flood would occur on average once in 30 years. In both 1972 and 1974, without flood control regulation, unregulated peak flows at The Dalles would have exceeded 28 300 m^3/s (1 000 000 cfs). The floods were regulated to approximately 17 000 m^3/s (600 000 cfs), the target flood specified in the Flood Control Operating Plan, as a result of flood storage operations throughout the Columbia River basin. The flood peak reductions achieved in actual operation of the Treaty project are shown as tables in Figs. 4-2 and 4-3.

It should be noted that:

1. During the summer of 1972, the Mica Project was in the early stages of construction and did not contribute to flood regulation at either Trail or The Dalles. The estimated unregulated peak of 10 600 m^3/s (375 000 cfs) at Trail in 1972 was regulated by the other Treaty projects to 7160 m^3/s (253 000 cfs).

2. In 1974, effective regulation of flows at the Mica Project was assured because the primary filling operation of the dead and live reservoir storage took place between 1973 and 1976. For this reason, the 10 600 m^3/s (375 000 cfs) unregulated peak at Trail in 1974 was regulated to 4420 m^3/s (156 000 cfs).

3. In 1976, the 4 August regulated peak flow at the Murphy Creek Project site was 5410 m^3/s (191 000 cfs). At this time surcharge of the Arrow Reservoir above El. 440.7 m (1446.0 ft) provided greater short-term regulation of the peak inflows than has been assumed in this study.

4.3 SENSITIVITY OF DESIGN FLOODS TO TREATY FLOOD CONTROL OPERATIONS

It was established in Section 2.0 that the need to use 'On Call' storage at the Mica Project to control floods at The Dalles in May and June could increase the July flood risk at the Murphy Creek Project site. This use of 'On Call' storage in May and June, which may be required to control flooding at the Dalles, could produce refill of Canadian storage prior to 31 July and this, in turn, could produce higher flood flows at the Murphy Creek Project site.

Because of the sensitivity of the flood risk to the regulation assumptions, the Murphy Creek Project flood frequency curve was defined in Section 2.5 as a composite of a low flood risk segment (represented by the regulated flood frequency curve derived in Section 2.4(a)), a high flood risk segment (represented by the regulated flood frequency curve derived in Section 2.4 (c)), and a transition section between these two segments. An issue that was not resolved concerned the determination of the full range of application of these three segments. The issue was unresolved because the frequency of need to implement the 1972 Columbia River Treaty Flood Control Operating Plan was not determined.

The need to implement the flood control plan is a complicated issue that depends upon the basin wide runoff volume forecast at The Dalles and the storage evacuation prior to the refill period. The criterion used in the flood control plan is defined in terms of the basin wide April-August flood volume that would occur once in 7 years and the Primary Storage. For basin wide flood volumes greater than the 7-year volume, it was assumed that 'On Call' storage would be needed for flood control at The Dalles. While the above could be used as a basis for selecting the transition segment of the Murphy Creek Project frequency curve, it does not adequately take account of the indirect flood control benefits which would automatically be derived at The Dalles from the winter power evacuation of 'On Call' storage. In this respect, the existing criterion does not distinguish between the expected frequency of use of 'On Call' storage for power generation (this would establish the frequency of storage evacuation), and the need to use 'On Call' storage to specifically serve flood control interests along the lower Columbia River (this would establish the frequency applying to the refill restrictions).

For the purposes of this report it was assumed that a 30-year flood would constitute a 'major' flood, and that the existing obligations for flood control, as defined in the 1972 Columbia River Flood Control Operating Plan, would require that the DDF and SDF discharges be based on the regulated flood frequency curve developed in Section 2.3(c) and not 2.3(a).

It should, however, be noted that the derivation of the Murphy Creek Project frequency curve is very sensitive to the flood control refill assumptions. It is possible that a reduction of up to 15 percent in the design flood discharges could be obtained if it could be shown that a modified flood control operation, achieving target date refill, would provide the same level of flood control effectiveness at The Dalles as is provided by the existing flood control plan.

If it could be guaranteed that upstream storage would be refilled on 31 July or later each year, then the 200-year SDF would be reduced from 7590 m^3/s (268 000 cfs) to 6460 m^3/s (228 000 c/s). Similarly, the 30-year DDF would be reduced from 6310 m^3/s (223 000 cfs) to 5490 m^3/s (194 000 cfs). These results demonstrate that the project design floods are sensitive to the potential shift in the regulated flood frequency curve (resulting from the regulation assumptions) as well as the adopted return period of the design floods. The return period sensitivity is indicated by the slope of the frequency curve.

4.4 SENSITIVITY OF DESIGN FLOODS TO MODIFIED OPERATING REGIMES

While detailed studies of alternative operations of the Keenleyside-Murphy Project have not been completed, two operating regimes have been investigated by the B.C. Hydro Generation Planning Department to determine maximized energy generation for these two projects. Regime 1 has been developed as a "base case" operation and Regime 2 has been developed as a modified operating plan based upon the AOP for the 1985-1986 operating year. The Murphy Creek Project operating regimes, based upon monthly simulations of the B.C. Hydro Columbia River System, provide data on project outflows, reservoir elevations and annual energy capability for the 35-year period of record 1940-1975.

For Regime 1, it was assumed that the development of the Keenleyside-Murphy Project would not significantly alter the operation of the Columbia River System. For Regime 2, it was assumed that the Arrow Lakes Reservoir would be operated at its highest level permitted by the existing flood control plan. This modified operation produces greater energy benefits for the Murphy Creek Project. The increased energy benefits were achieved by retaining at least 2.5 x 10^9m^3 (2.0 Maf) in live storage at the Keenleyside Project in most years. This is permitted as a result of the 5:2 split of Primary Flood Control Storage between the Keenleyside and Mica projects.

While the 31 July target date flood frequency curve developed in Section 2.4(a) was based upon the regulation assumption that AOP's would provide a sufficiently flexible operating framework for achieving target date refill, the derivation of the flood frequency curve did not specifically consider losses in operating flexibility in July that could arise with the implementation of Regime 2. It is possible that Regime 2 could be implemented in years of above average runoff without changing the regulated flood frequency curve developed in Section 2.4(a). A more likely result of implementing Regime 2 in years of above average runoff would be that the Murphy Creek Project flood frequency curve would be defined over a broader return period range by the high flood risk frequency curve (Section 2.4(c)).

In general, a loss of operating flexibility will occur in July in major flood years, and for this reason, the Predetermined and Updated Flood Control frequency curves developed in Sections 2.4(b) and 2.4(c) were based upon a relatively narrow interpretation of the requirements of the flood control plan. An option that would provide increased operational flexibility in major flood years would be to use non-Treaty flood storage space to achieve additional Canadian flood protection. This was not extensively evaluated in the derivation of flood peak estimates. The approximate volume of non-Treaty storage available for this purpose at the Keenleyside Project is 0.32 x $10^9 m^3$ (0.26 Maf). In addition, and as a result of a 1979 storage transfer agreement, 0.65 x $10^9 m^3$ (0.53 Maf) of non-Treaty storage was developed by reducing the target full pool elevation at the Mica Project. When the Revelstoke Project becomes operational, approximately 0.52 x $10^9 m^3$ (0.42 Maf) of storage at this project could also be used for Canadian flood control purposes. The flood control benefits of using this non-Treaty storage would have to be balanced against potential losses in energy benefits.

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For Regime 1, it was assumed that the development of the Keenleyside-Murphy Project would not significantly alter the operation of the Columbia River System. For Regime 2, it was assumed that the Arrow Lakes Reservoir would be operated at its highest level permitted by the existing flood control plan. This modified operation produces greater energy benefits for the Murphy Creek Project. The increased energy benefits were achieved by retaining at least 2.5 x $10^9 m^3$ (2.0 Maf) in live storage at the Keenleyside Project in most years. This is permitted as a result of the 5:2 split of Primary Flood Control Storage between the Keenleyside and Mica projects.

While the 31 July target date flood frequency curve developed in Section 2.4(a) was based upon the regulation assumption that AOP's would provide a sufficiently flexible operating framework for achieving target date refill, the derivation of the flood frequency curve did not specifically consider losses in operating flexibility in July that could arise with the implementation of Regime 2. It is possible that Regime 2 could be implemented in years of above average runoff without changing the regulated flood frequency curve developed in Section 2.4(a). A more likely result of implementing Regime 2 in years of above average runoff would be that the Murphy Creek Project flood frequency curve would be defined over a broader return period range by the high flood risk frequency curve (Section 2.4(c)).

In general, a loss of operating flexibility will occur in July in major flood years, and for this reason, the Predetermined and Updated Flood Control frequency curves developed in Sections 2.4(b) and 2.4(c) were based upon a relatively narrow interpretation of the requirements of the flood control plan. An option that would provide increased operational flexibility in major flood years would be to use non-Treaty flood storage space to achieve additional Canadian flood protection. This was not extensively evaluated in the derivation of flood peak estimates. The approximate volume of non-Treaty storage available for this purpose at the Keenleyside Project is 0.32 x $10^9 m^3$ (0.26 Maf). In addition, and as a result of a 1979 storage transfer agreement, 0.65 x $10^9 m^3$ (0.53 Maf) of non-Treaty storage was developed by reducing the target full pool elevation at the Mica Project. When the Revelstoke Project becomes operational, approximately 0.52 x $10^9 m^3$ (0.42 Maf) of storage at this project could also be used for Canadian flood control purposes. The flood control benefits of using this non-Treaty storage would have to be balanced against potential losses in energy benefits.

SECTION 5.0 - CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

It was concluded that:

1. The Murphy Creek Project flood frequency curve is dependent upon the regulation assumptions concerning the operation of upstream Columbia River Treaty projects (Sections 1.3, 1.5, 2.1, 2.4, 2.5, 3.4, 4.3, and 4.4).

2. Under conditions of high basin-wide flood risk, the flood risk at the Murphy Creek Project site would be derived from reservoir operations required by the 1972 Columbia River Treaty Flood Control Operating Plan. Two possible regulated flood frequency curves were derived for these conditions and, of these two curves, the one which took account of the local Flood Control objective at Trail defines the upper return period portion of the project flood frequency curve (Sections 2.1, 2.4, 2.5, 4.3, and 4.4).

3. Under conditions of low basin wide flood risk, the flood risk at the Murphy Creek Project site would be derived from Assured Operating Plans based upon a 31 July refill date. This regulated flood frequency curve defines the lower return period portion of the project flood frequency curve (Sections 2.1, 2.4, 2.5, 4.3, and 4.4).

4. The transition between the lower and upper portions of the project flood frequency curve occurs between the 10- and 30-year return periods, approximately corresponding to the likely onset of 'On Call' storage use for basin-wide flood control (Sections 2.5, 4.3, and 4.4).

5. The flood simulation analyses verified and supplemented the flood frequency analyses developed from the 1913-1979 streamflow data. In particular, these flood simulation analyses assessed the regulation of high flood events similar to those known to have occurred in 1880, 1887, and 1894, which were recorded at the Dalles (Sections 1.5, 3.1, and 4.1).

6. The flood risk at the Murphy Creek Project would not simply be dependent on flood volumes, but would also be dependent on the time distribution of runoff and the use of flood storage space as defined in the 1972 Columbia River Flood Control Operating Plan (Sections 3.2, 3.3, and 4.1).

7. The need to use 'On Call' storage at the Mica Project to control floods at the Dalles in May and June could increase the late July flood risk at the Murphy Creek Project (Sections 2.1, 2.5, and 4.3).

8. The key to effective flood regulation at the Murphy Creek Project would be a modified July operation of 'On Call' storage at the Mica Project. If this modified July operation were possible, then a reduction of up to 15 percent in the design flood discharges for the Murphy Creek Project could be obtained. Such a flood control operation, which would achieve target date refill (31 July), must be shown to provide the same level of flood control effectiveness at The Dalles as is provided by the existing flood control plan (Sections 4.3, and 4.4).

9. The flood control objective of reducing the flood hazard along the main stem of the Columbia River, and, in particular, the control of floods to less than the existing 7930 m^3/s major flood control objective at Castlegar/Trail would justify the implementation of additional operational measures to compensate for errors in flood volume forecasting at the Mica Project (Sections 2.1, and 2.4).

10. The adoption of Operating Regime 2, which would enhance winter and spring power generation at the Murphy Creek Project, would be consistent with the selection of the DDF and SDF discharges from the high flood risk segment of the project flood frequency curve (Section 4.4).

5.2 RECOMMENDATIONS

It is recommended that:

1. The Regulated Flood Frequency Curve as developed in Section 2.4(c) be adopted for project design. The curve is given below and is plotted in Fig. 2-1.

Regulated Flood Frequency Curve for Project Design

Return Period (years)	Regulated Flood Peak (m^3/s)	Regulated Flood Peak (cfs)
5*	(4 950)	(175 000)
30	6 310	223 000
100	7 130	252 000
200	7 590	268 000
500*	(8 150)	(288 000)

Note: * The Murphy Creek Project flood frequency curve is only partially derived from the Updated Flood Control frequency curve (2.4(c)) and does not strictly apply at these return periods. See Fig. 2-1.

2. The 200-year flood of 7590 m^3/s be selected as the Spillway Design Flood. This discharge would be used, in project design, to achieve the flood control level objectives at Castlegar.

3. The 30-year flood of 6310 m^3/s be tentatively selected as the Diversion Design Flood. The final selection of the DDF will be based on economic analysis, and is outside the scope of this report.

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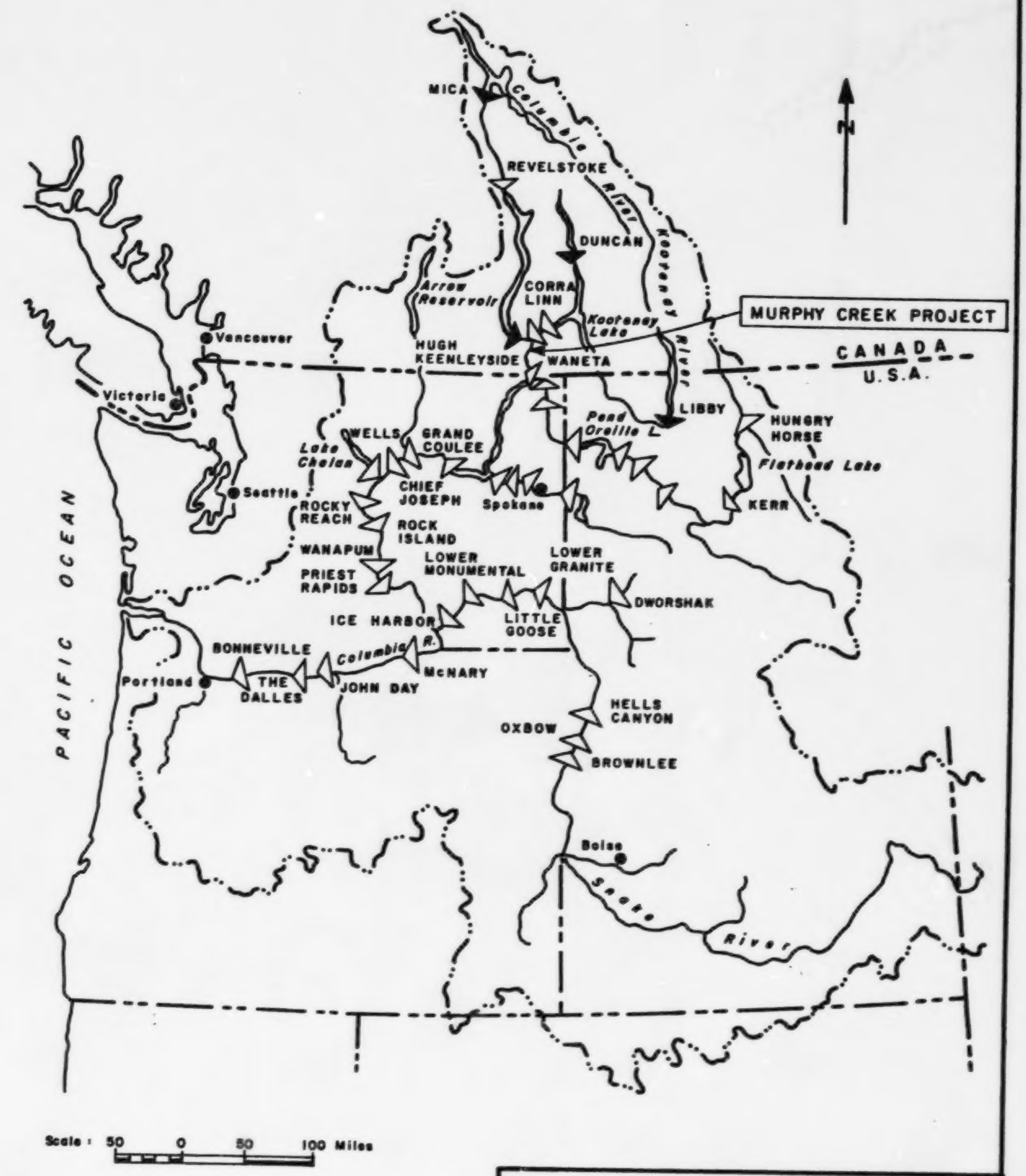

MICA
Columbia River
REVELSTOKE
N
DUNCAN
Kootenay River
Arrow Reservoir
CORRA LINN
Kootenay Lake
MURPHY CREEK PROJECT
Vancouver
HUGH KEENLEYSIDE
WANETA
CANADA
U.S.A.
Victoria
LIBBY
HUNGRY HORSE
Pend Oreille L.
WELLS
GRAND COULEE
Lake Chelan
Flathead Lake
CHIEF JOSEPH
Spokane
Seattle
KERR
ROCKY REACH
ROCK ISLAND
PACIFIC OCEAN
WANAPUM
LOWER MONUMENTAL
LOWER GRANITE
PRIEST RAPIDS
DWORSHAK
ICE HARBOR
LITTLE GOOSE
BONNEVILLE
Columbia R.
McNARY
Portland
THE DALLES
JOHN DAY
HELLS CANYON
OXBOW
BROWNLEE
Boise
Snake River
Scale: 50 0 50 100 Miles

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

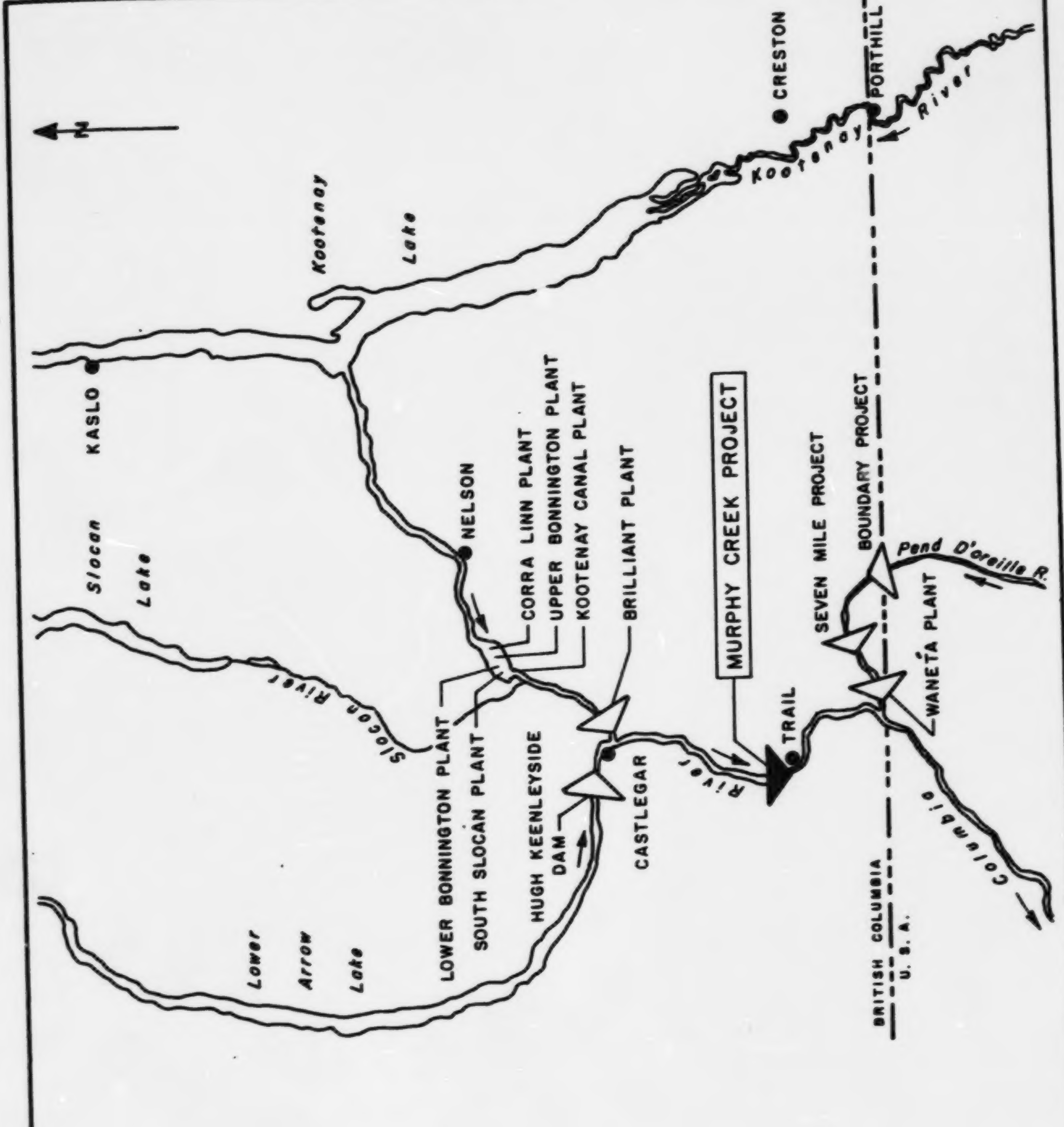
LEGEND

◀ *Treaty projects*

◁ *Other projects*

MAP OF THE COLUMBIA RIVER BASIN

DATE MAY 1980	FIG. 1-1
DWN D.J.	DWG No.


N
CRESTON
PORTHILL
Kootenay River
Kootenay Lake
KASLO
Slocan Lake
NELSON
CORRA LINN PLANT
UPPER BONNINGTON PLANT
KOOTENAY CANAL PLANT
BRILLIANT PLANT
MURPHY CREEK PROJECT
SEVEN MILE PROJECT
BOUNDARY PROJECT
Pend D'oreille R.
WANETA PLANT
TRAIL
River
Slocan River
LOWER BONNINGTON PLANT
SOUTH SLOCAN PLANT
HUGH KEENLEYSIDE DAM
CASTLEGAR
Lower Arrow Lake
Columbia
BRITISH COLUMBIA
U. S. A.

LEGEND

▷ *Existing Projects*

◀ *Proposed Project*

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

LOCATION OF THE MURPHY CREEK PROJECT

DATE MAY 1980	FIG 1-2
DWN D.J.	DWG No.

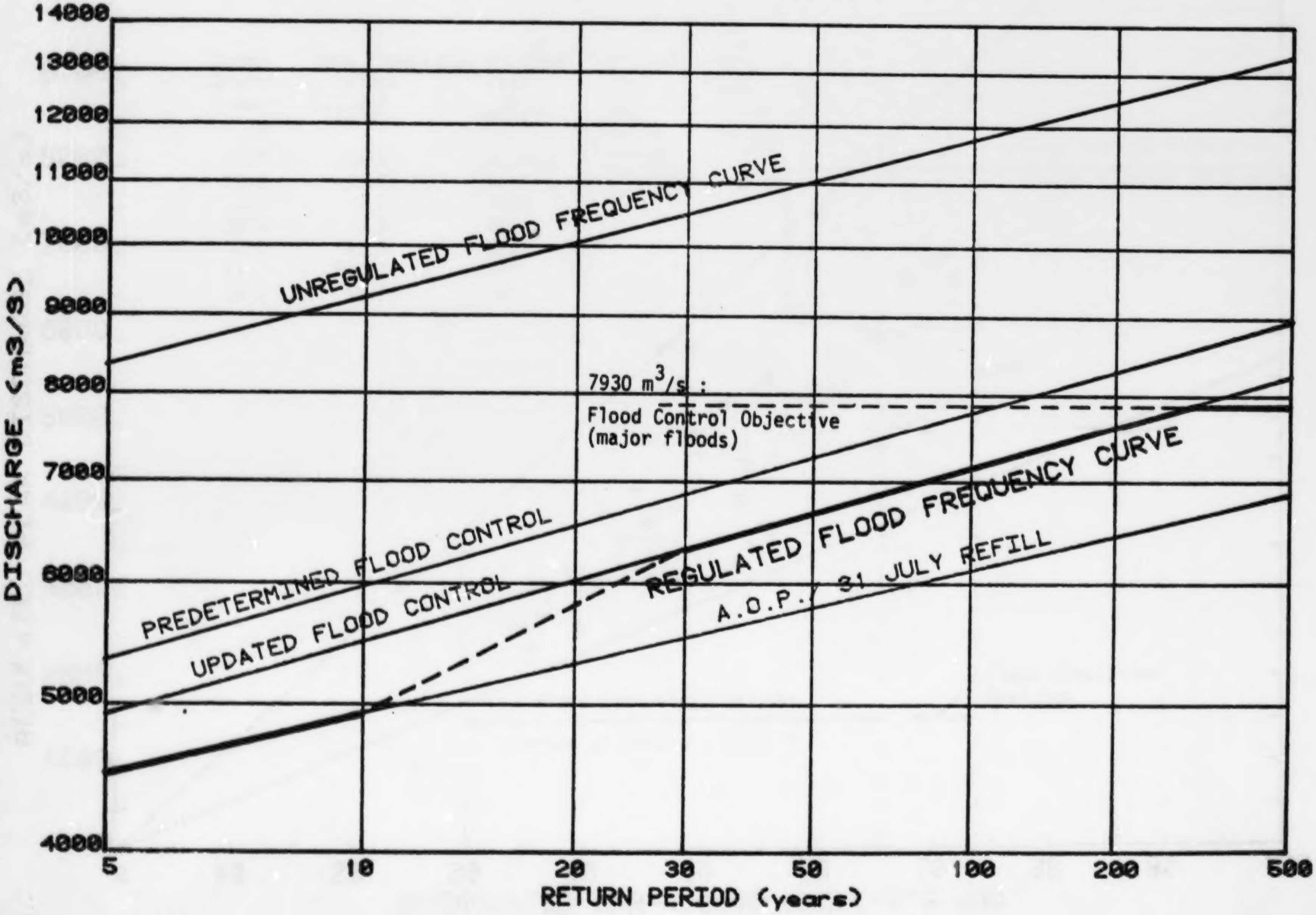
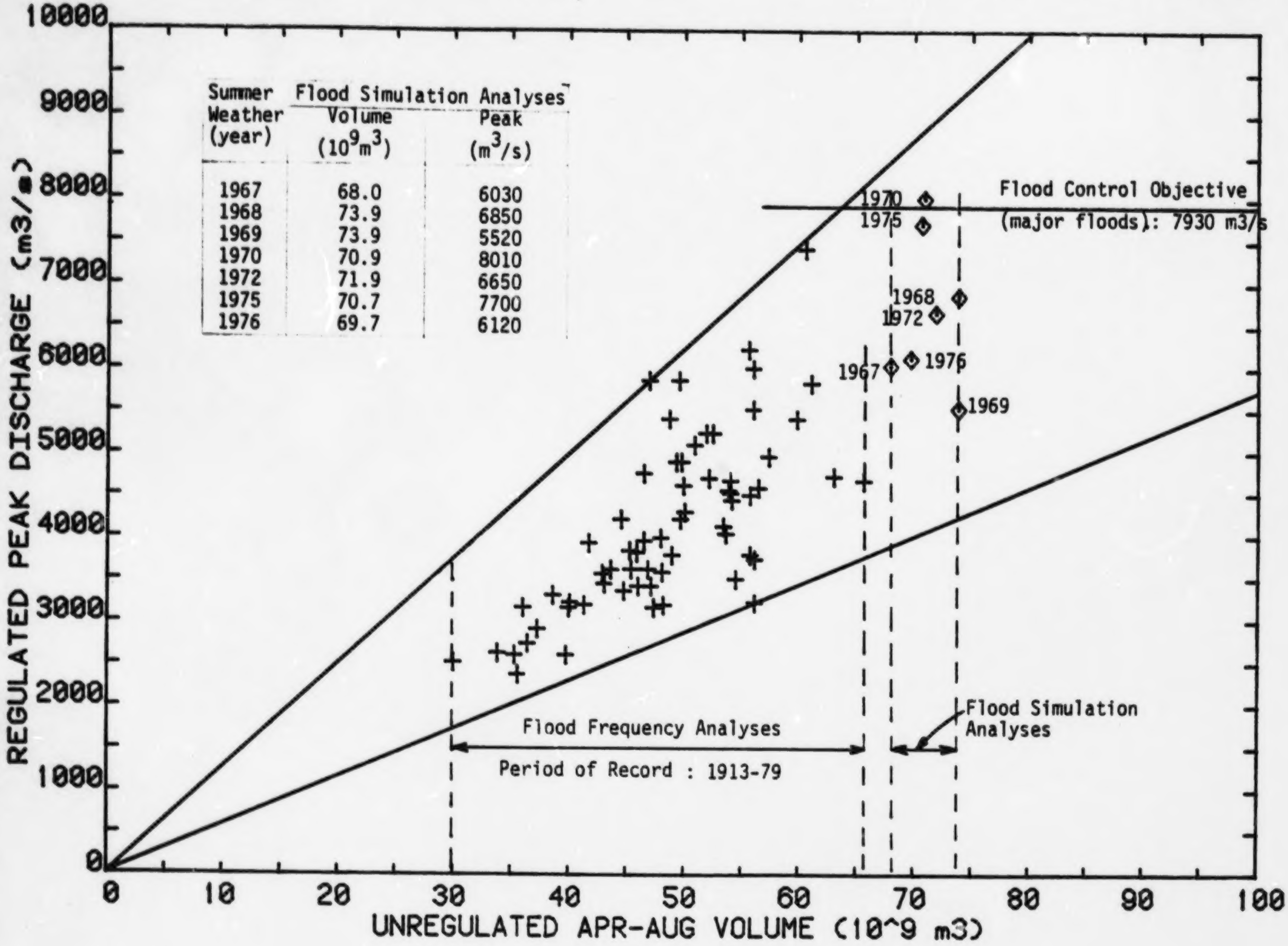
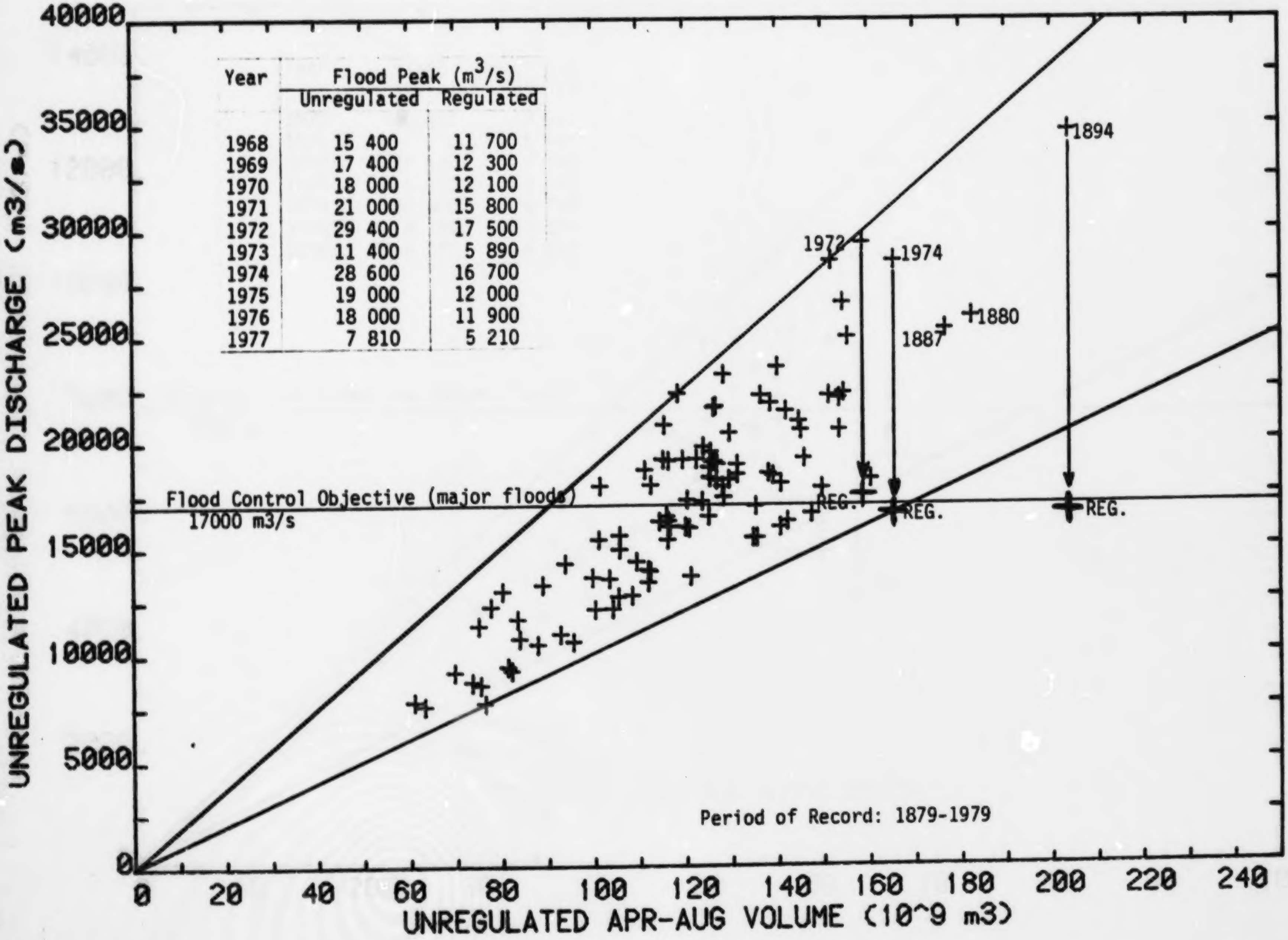


FIG. 2-1: FLOOD FREQUENCY CURVES - MURPHY CREEK PROJECT SITE



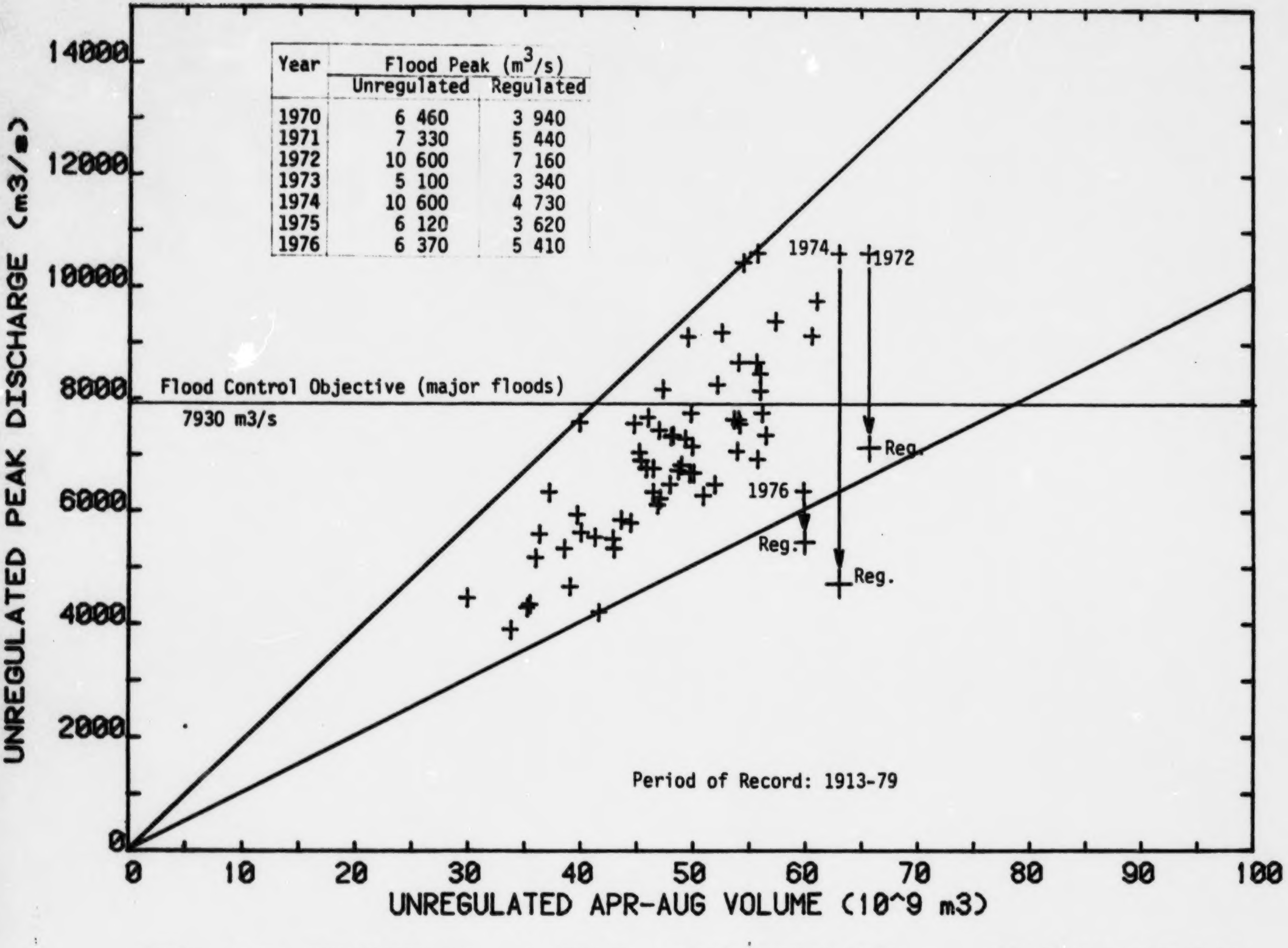
Summer Weather (year)	Flood Simulation Analyses Volume ($10^9 m^3$)	Peak (m^3/s)
1967	68.0	6030
1968	73.9	6850
1969	73.9	5520
1970	70.9	8010
1972	71.9	6650
1975	70.7	7700
1976	69.7	6120

FIG. 4-1: MURPHY CREEK PROJECT: REGULATED PEAKS VS. FLOOD VOLUME



Year	Flood Peak (m^3/s)	
	Unregulated	Regulated
1968	15 400	11 700
1969	17 400	12 300
1970	18 000	12 100
1971	21 000	15 800
1972	29 400	17 500
1973	11 400	5 890
1974	28 600	16 700
1975	19 000	12 000
1976	18 000	11 900
1977	7 810	5 210

FIG. 4-2: COLUMBIA R. at THE DALLES: PEAK DISCHARGE vs. SEASONAL VOLUME



Year	Flood Peak (m^3/s)	
	Unregulated	Regulated
1970	6 460	3 940
1971	7 330	5 440
1972	10 600	7 160
1973	5 100	3 340
1974	10 600	4 730
1975	6 120	3 620
1976	6 370	5 410

FIG. 4-3: COLUMBIA R. at TRAIL: PEAK DISCHARGE vs. SEASONAL VOLUME

POOR

QUALITY

ORIGINAL